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Virtual Seismometers in Geothermal Systems: Looking Inside the Microseismic Cloud

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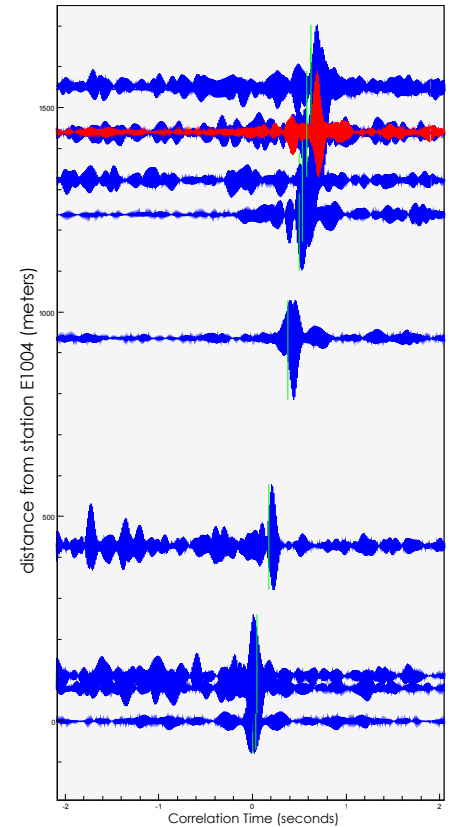
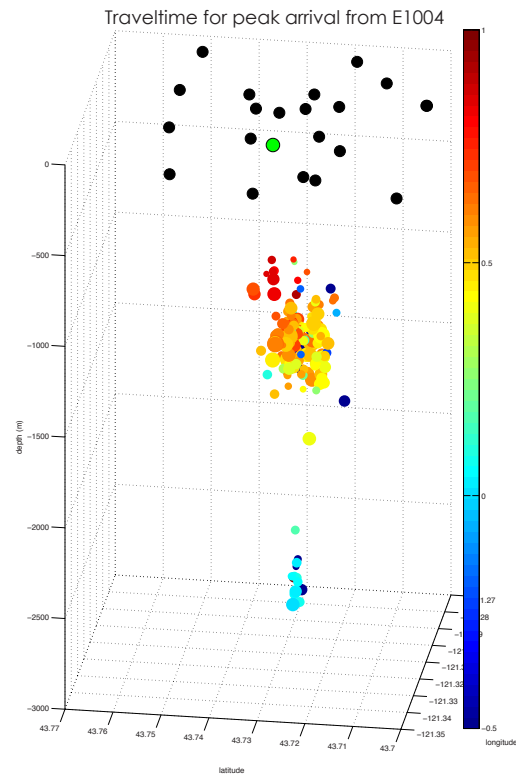
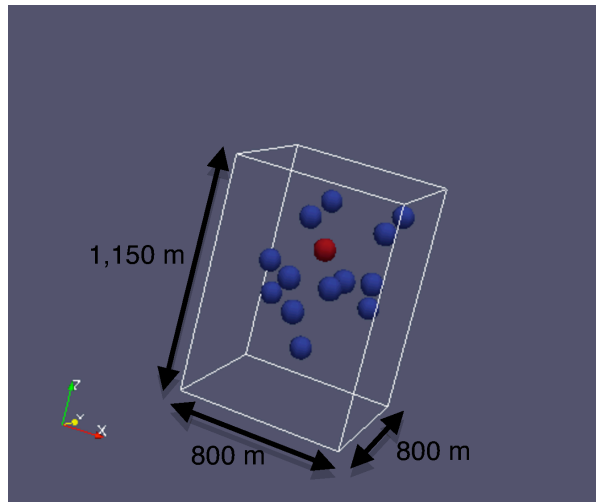
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Virtual Seismometers in Geothermal Systems: Looking Inside the Microseismic Cloud



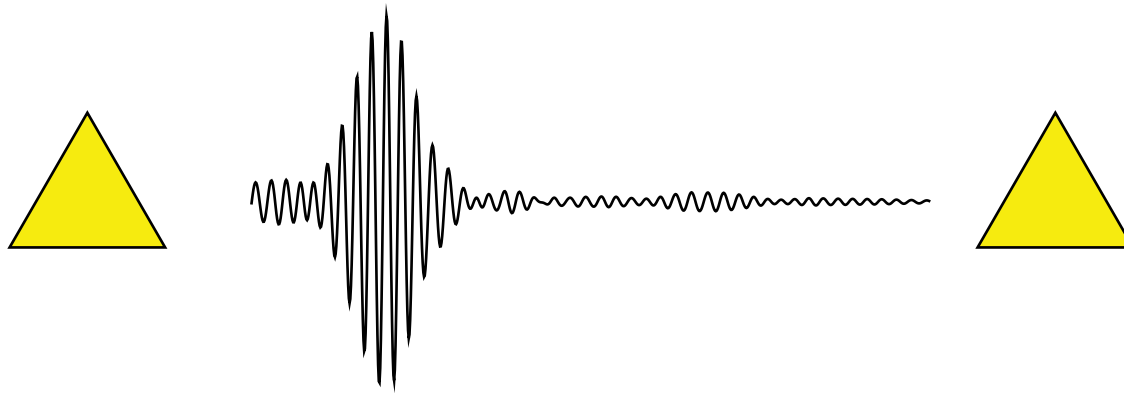
Eric Matzel, Christina Morency, Andrea Rhode, Dennise Templeton and Moira Pyle

Lawrence Livermore National Laboratory

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LLNL-CONF-683265

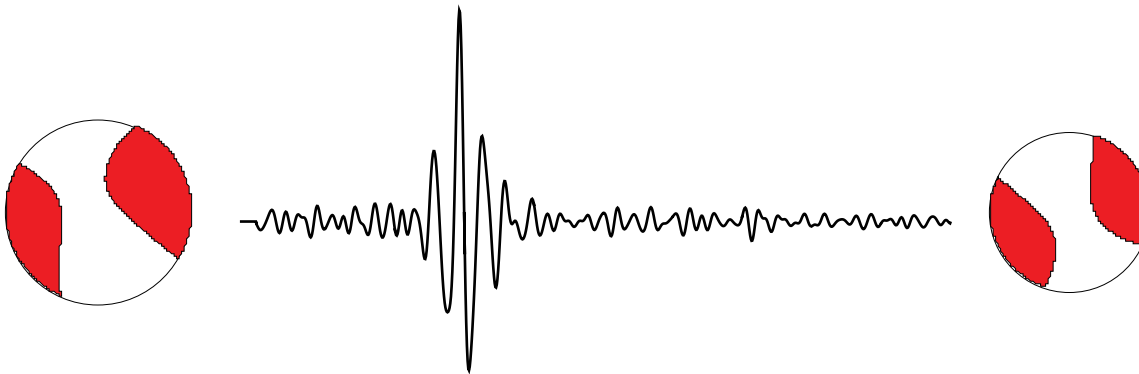
The virtual seismometer method (VSM) is the converse of ambient noise correlation (ANC)



ANC

"virtual earthquake"

$$CC = GF_{AB}$$



VSM

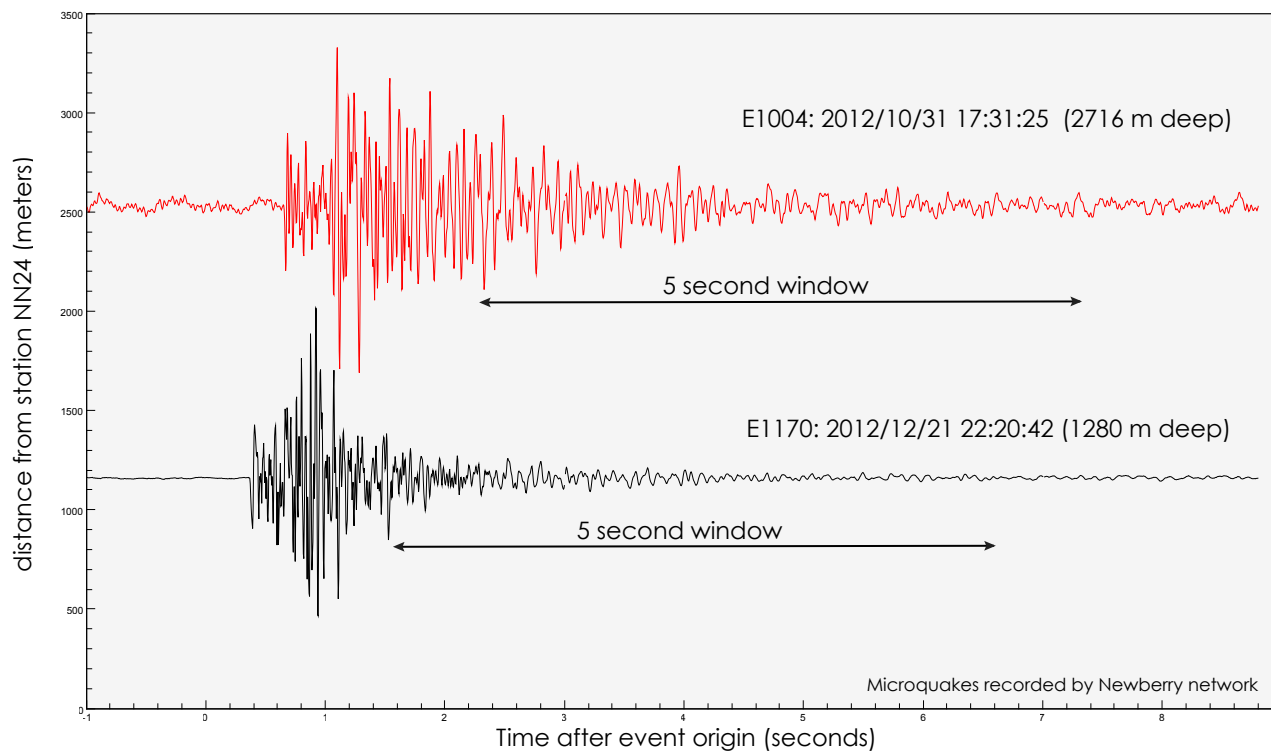
"virtual seismometer"

$$CC = M_1 M_2 GF_{12}$$

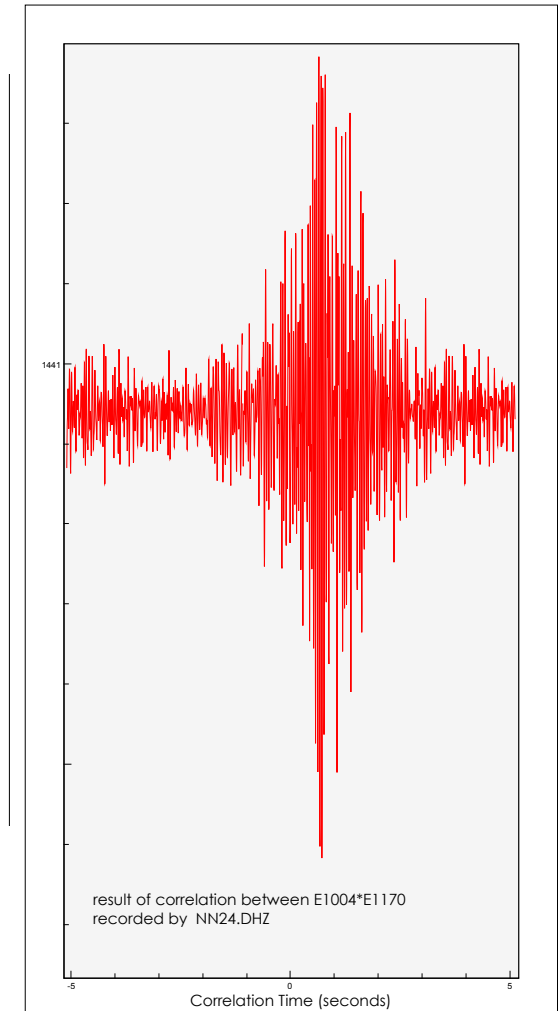
Both methods: $N_{\text{correlations}} = N(N-1)/2$

How to turn a microquake into a virtual seismometer

- Obtain the data for 2 earthquakes recorded by a single station
- At Newberry, we isolated 5 second long windows within the coda of each microquake.
- Correlate the coda traces.
- Repeat for all stations in the network.



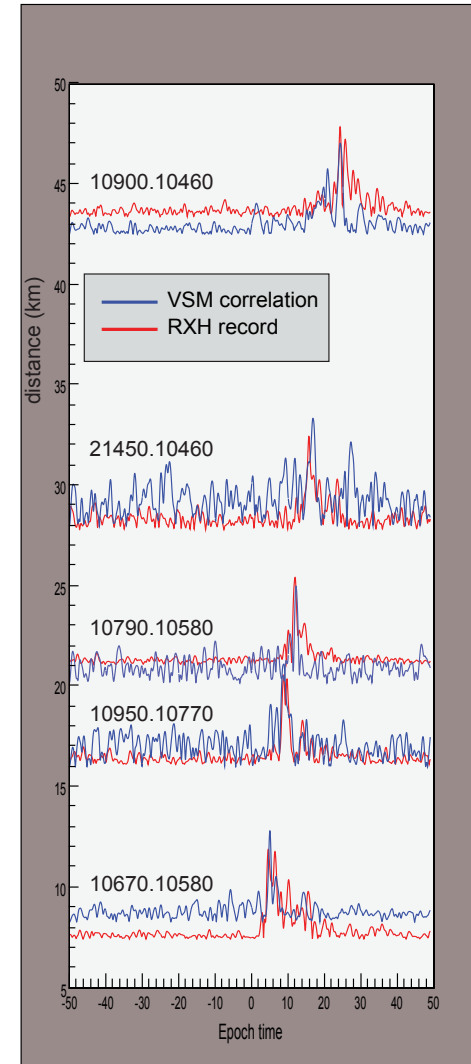
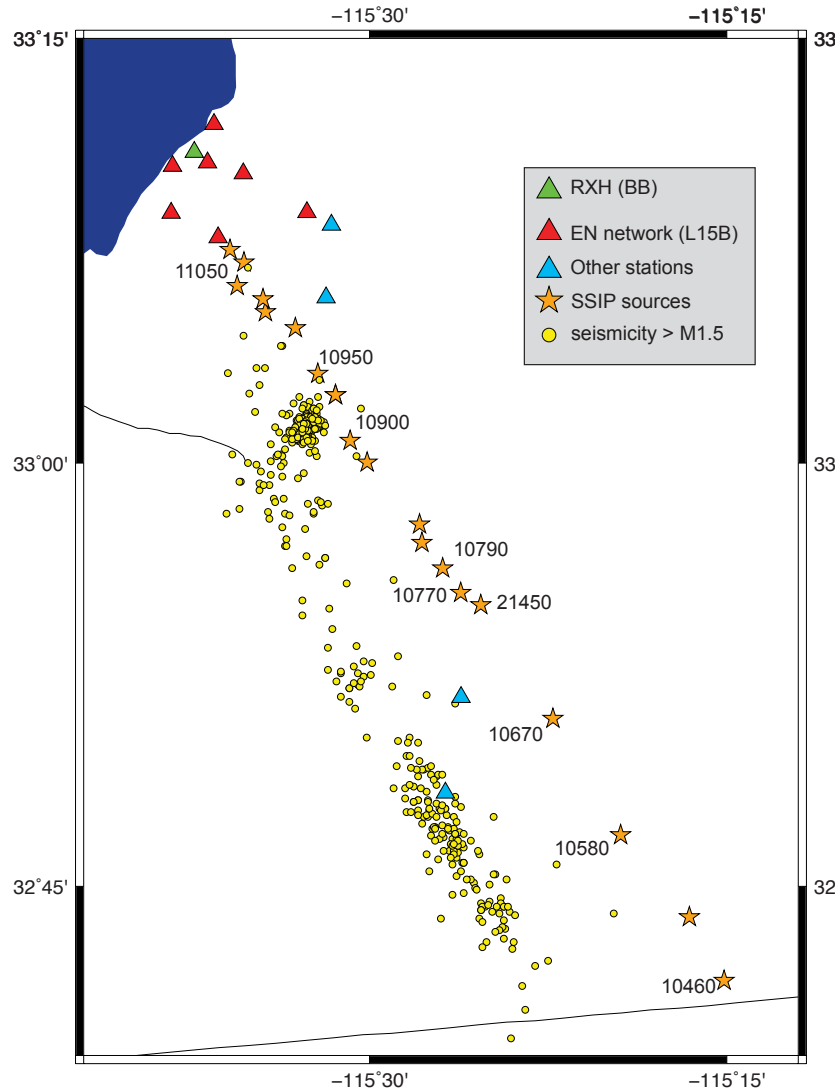
Correlation of 2 microquakes separated by 1440 meters recorded by NN24



Virtual seismograms in the local field

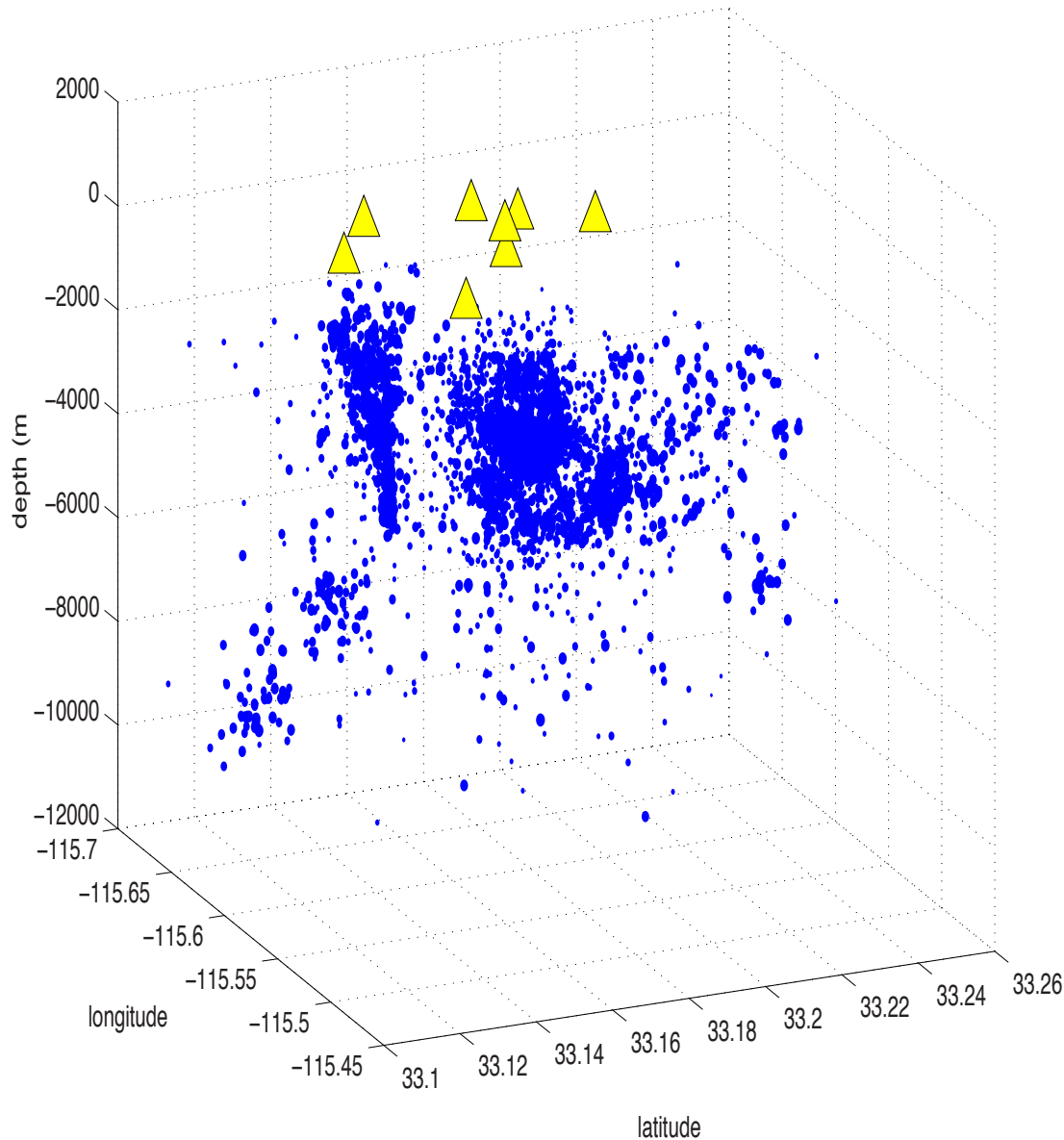
(distance between quakes ~ distance to recording network)

Virtual seismograms compare well against records at the Salton Sea



Above: SSIP data recorded at broadband station RXH(red) are compared to virtual seismograms created using the correlation of the SSIP sources (blue). All traces were filtered between 4-5 Hz.

Moving into the near field: Applying VSM to microseismic records (distance between quakes > distance to recording network)

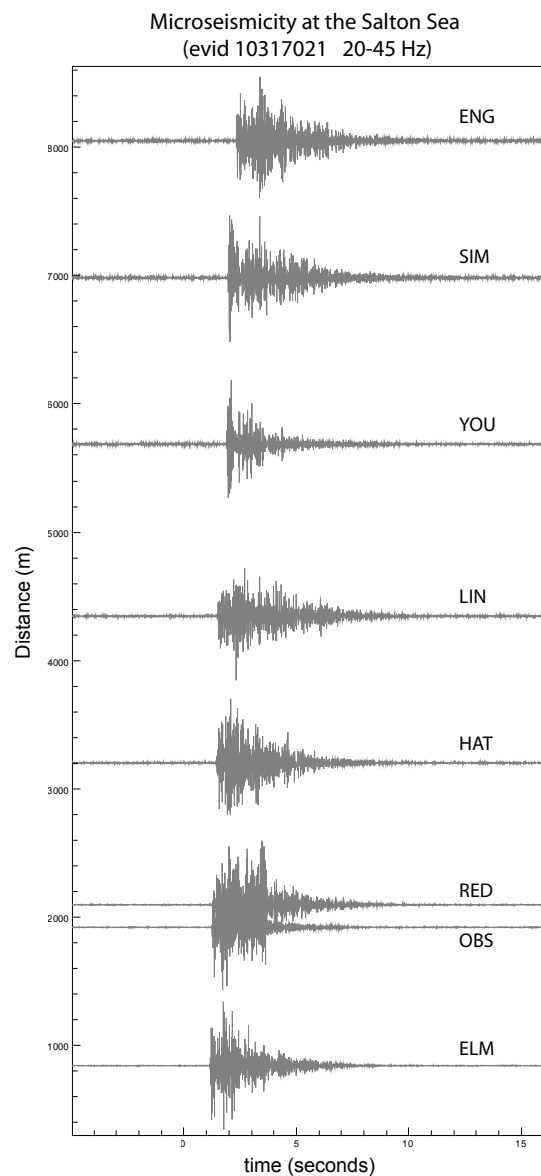
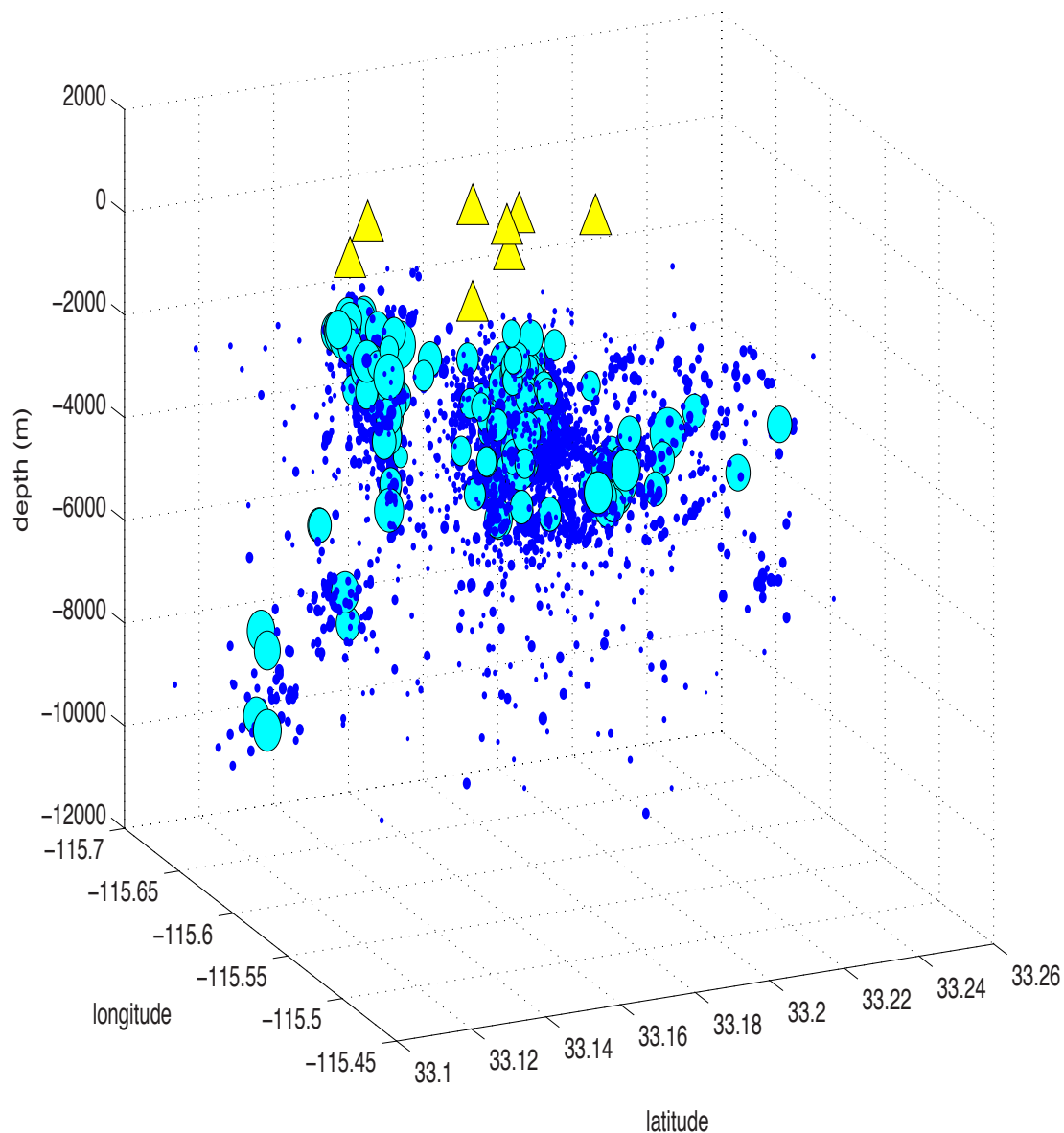


Hauksson catalog of events 2008-2011

- Thousands of microseismic events occur beneath the Salton Sea geothermal fields.
- This cloud of microseismicity effectively illuminates the subsurface.
- Millions of potential interferometric measurements.

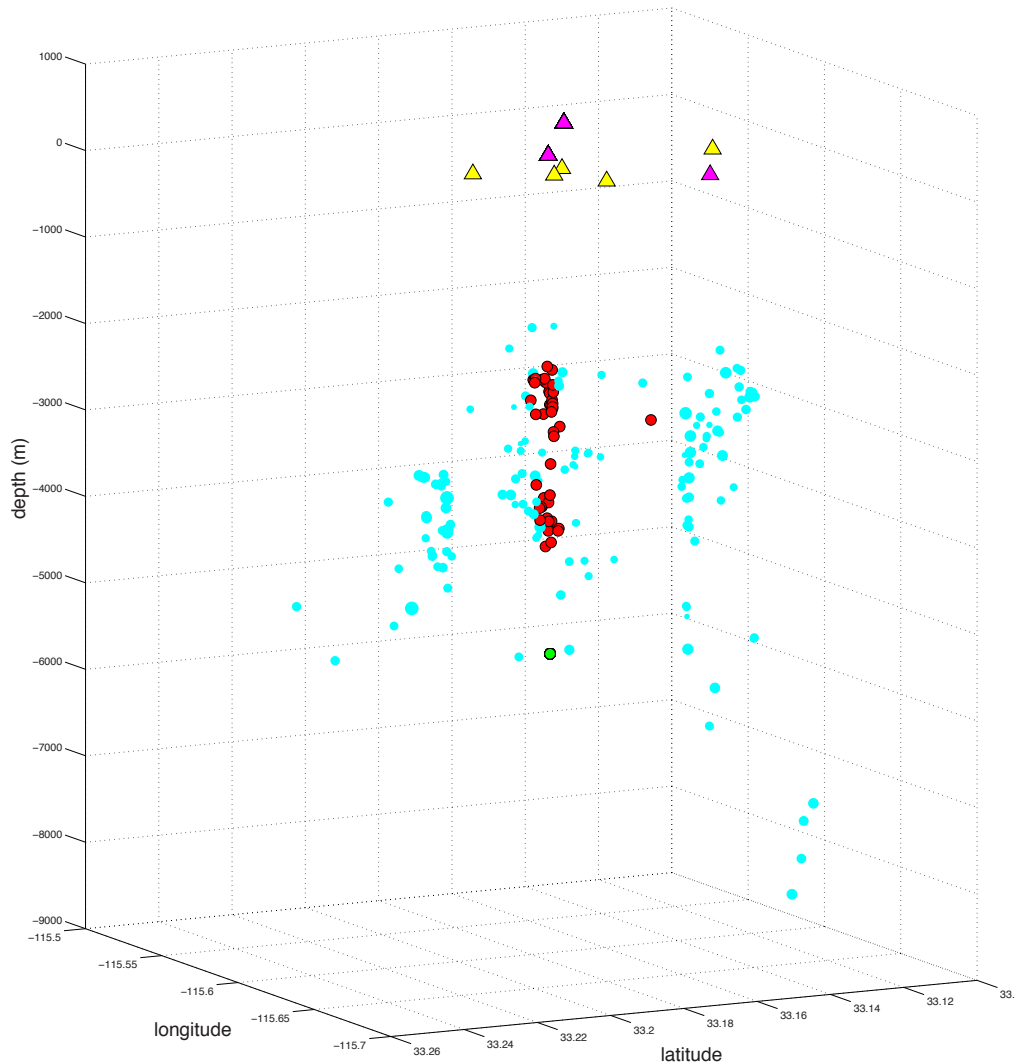
$$N_{\text{correlations}} = N*(N-1)/2$$

Focusing on the a well distributed collection of high quality events



183 template events within the microseismic cloud (Wang et al., 2015)

VSM is sensitive to the geometry of the system



Coda interferometry can be done between all events in the system.

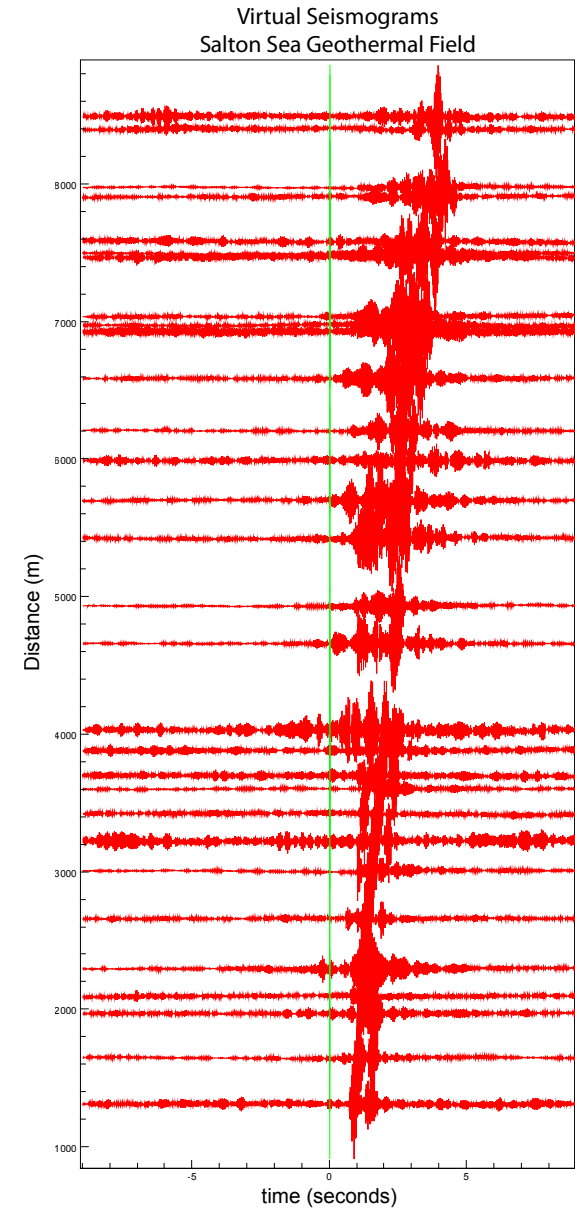
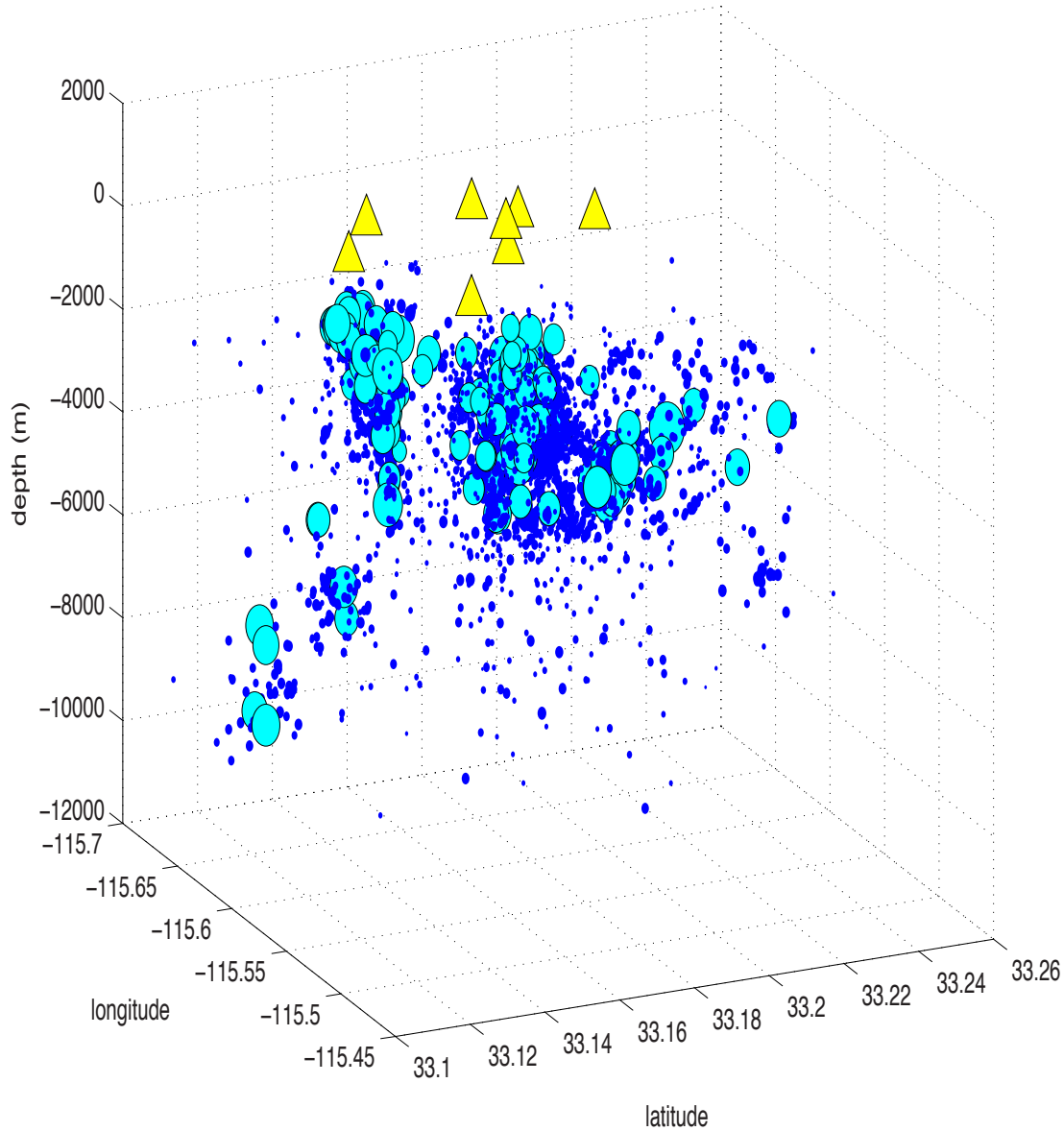
When the events fall along a line pointing to the recording station:

VSM = estimate of the Green function (GF) between earthquakes.

183 template events:
> 16,000 correlations
~ 1500 virtual seismograms

Example of the ideal geometry for obtaining virtual seismograms

Example of virtual seismograms at the Salton Sea

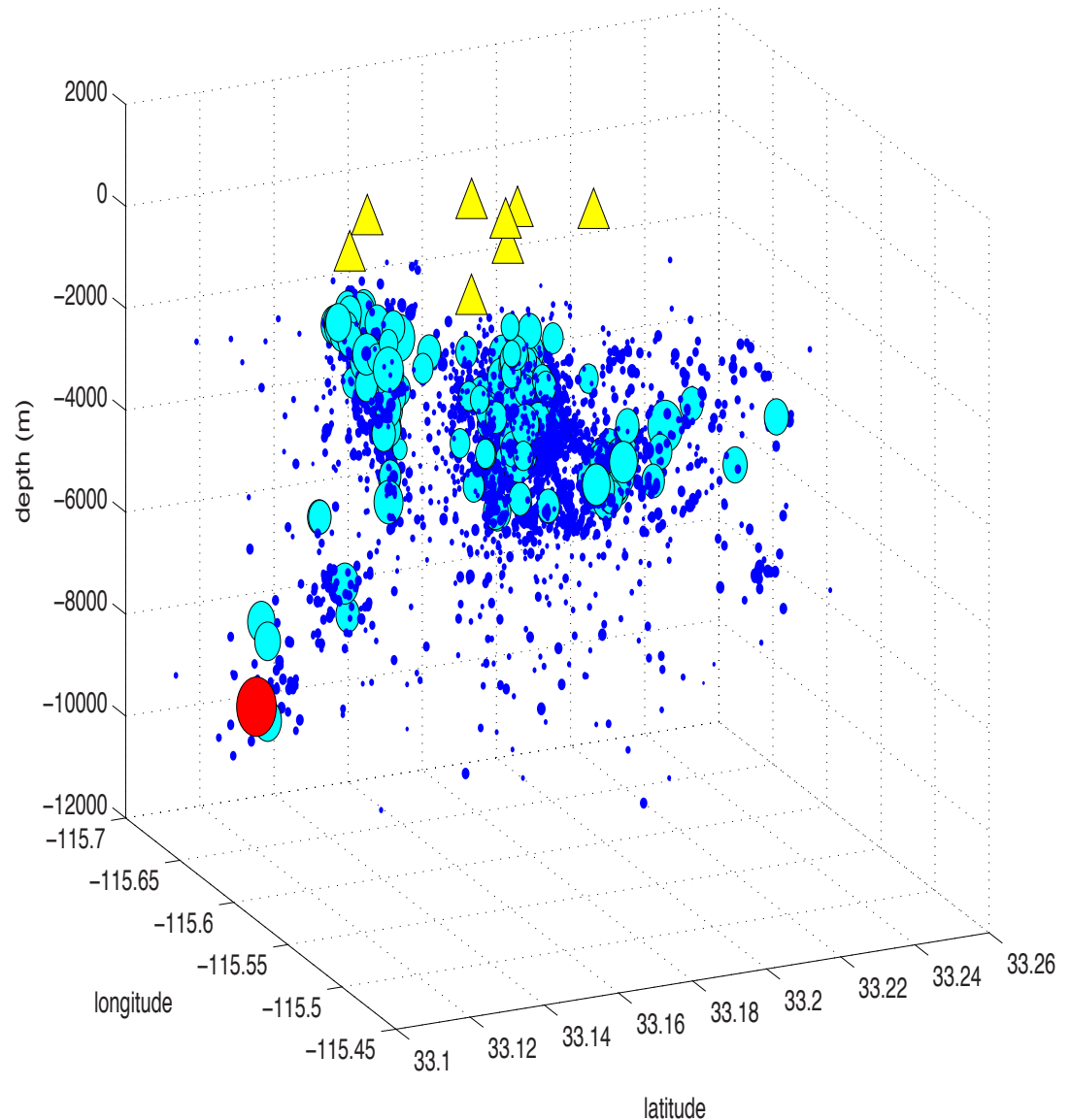
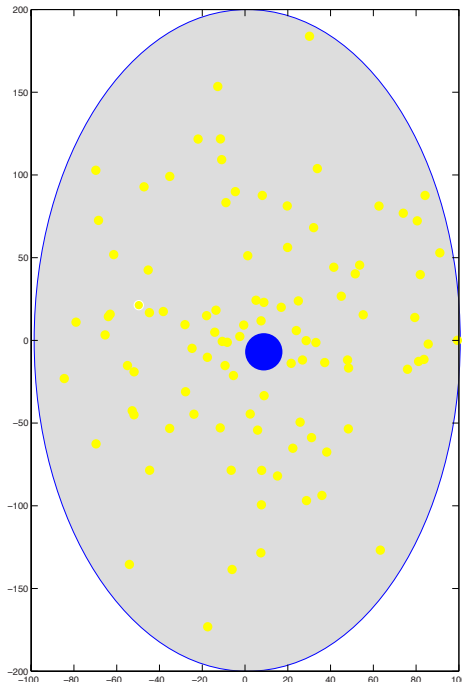


183 template events within the microseismic cloud (Wang et al., 2015)

Moving into the very near field
(when the quakes fall within the same uncertainty ellipse)

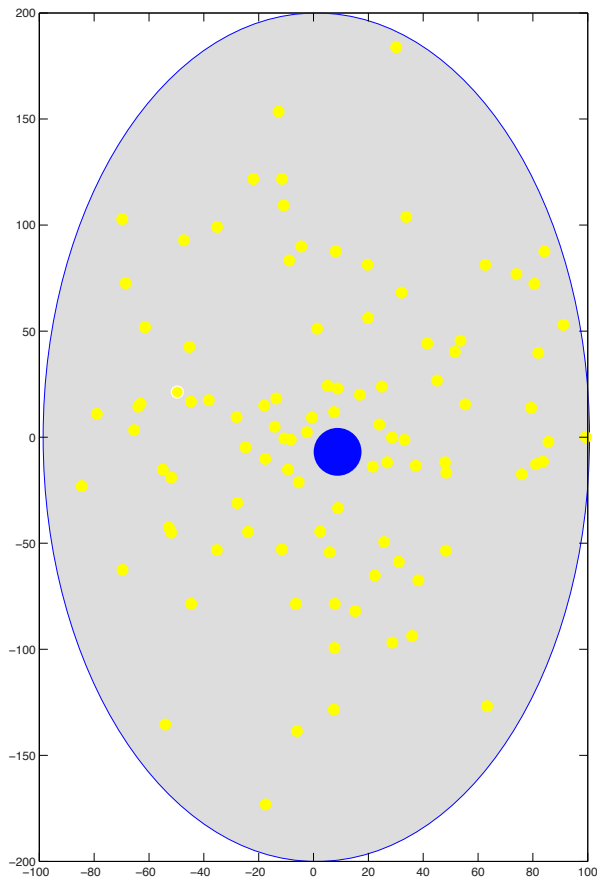
Pushing the limits on
resolution and magnitude.

At this range:
Lose constraints on the
geometry.

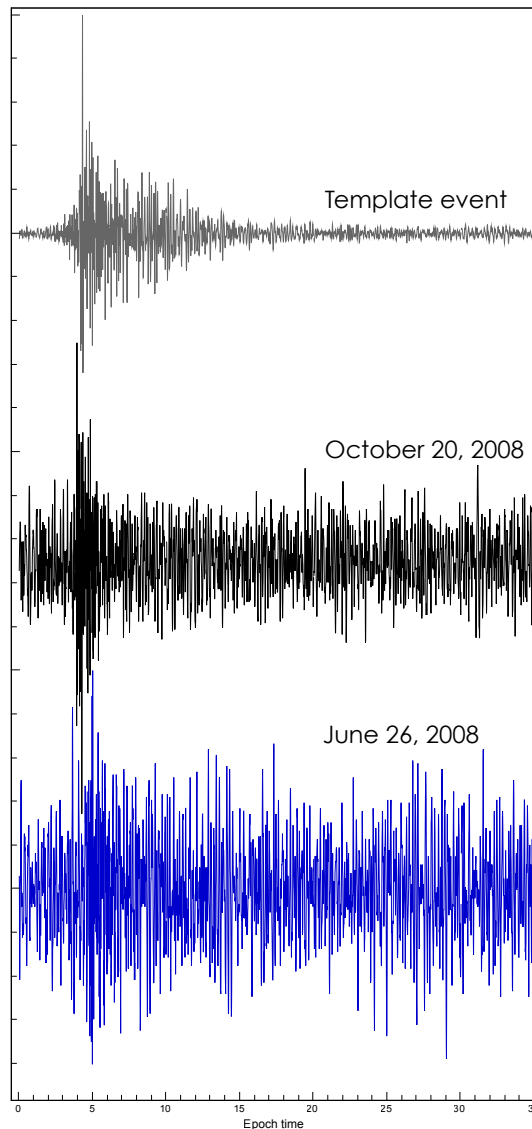


Moving into the very near field (when the quakes fall within the same uncertainty ellipse)

MFP template and detected events

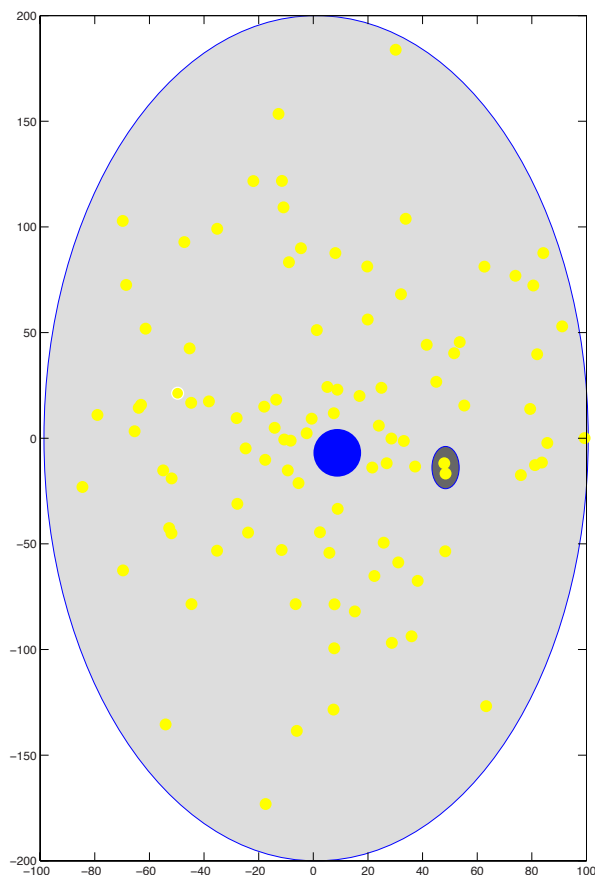


A template event can be used to detect smaller events nearby



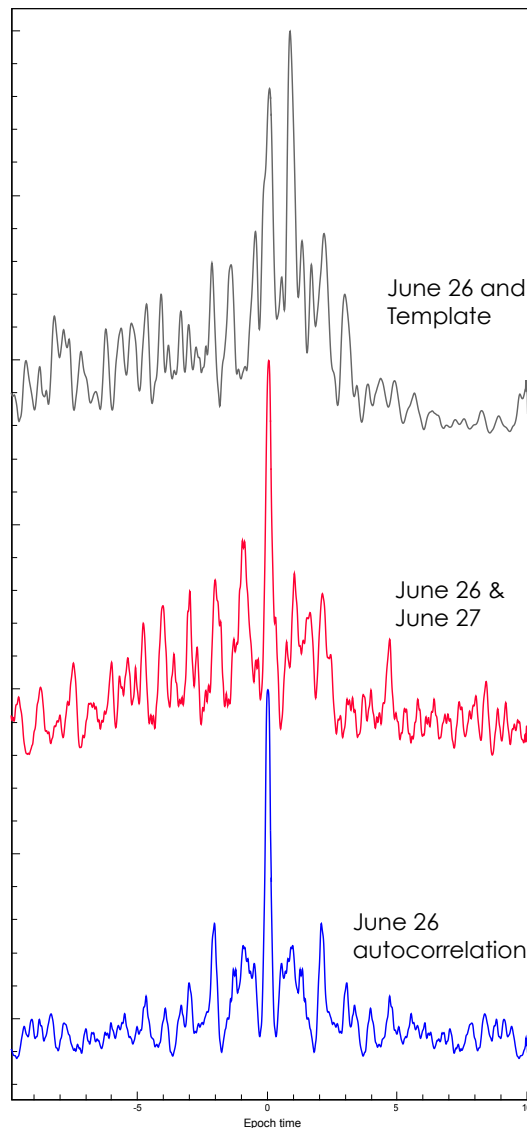
- MFP identifies signals that match the template event across all stations, channels and frequency bands.
- The template shown detected 77 additional events, many of which were buried in the background noise.
- We expect these to be spatially close to the template event.

The symmetry and structure of the correlation allow us to sort the events in space.



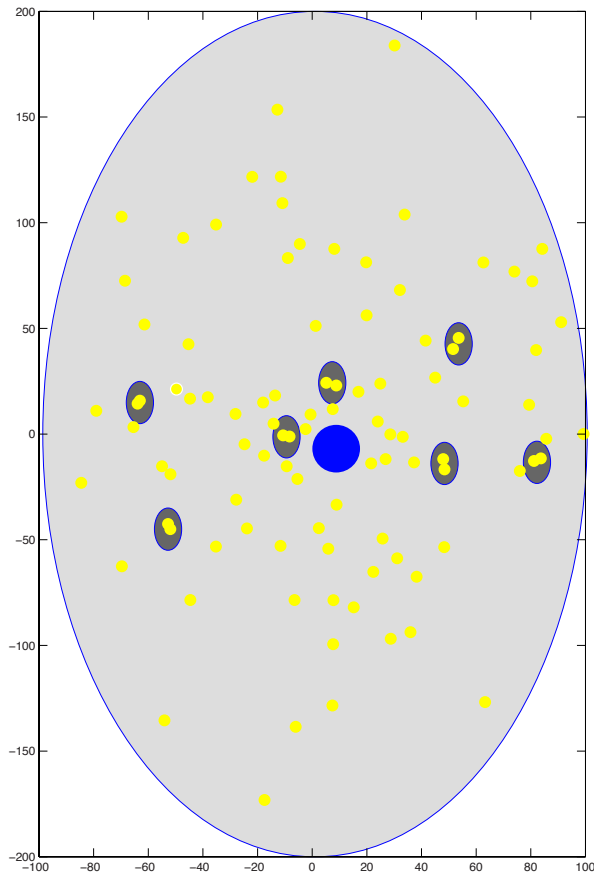
A pair of closely spaced events in the MFP population.

Coda Correlation



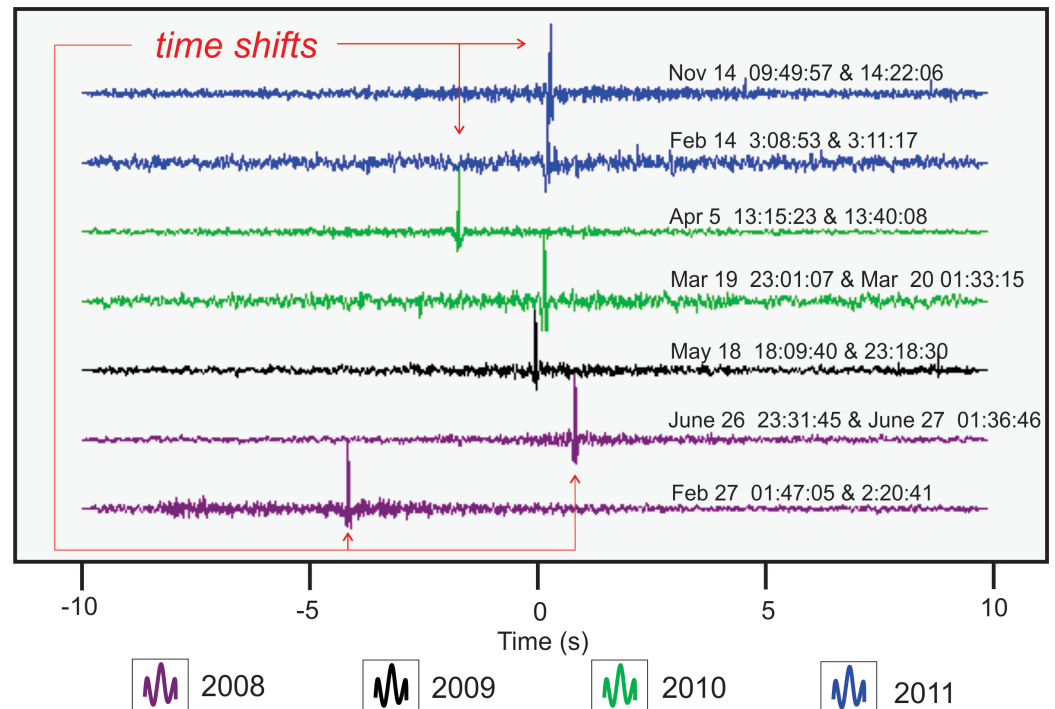
- Correlation of closely spaced events will appear similar to an autocorrelation.
- Correlation of events separated in space will be assymmetric and include multiple peaks.
- Detected events often correlate better with one another than with the original template event.

Subclusters emerge from the MFP population.

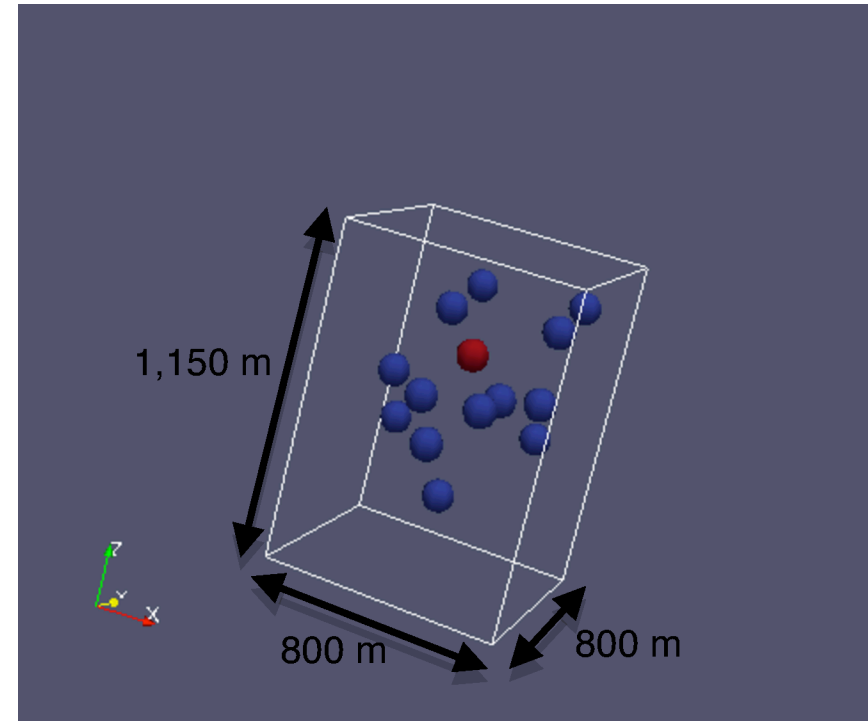
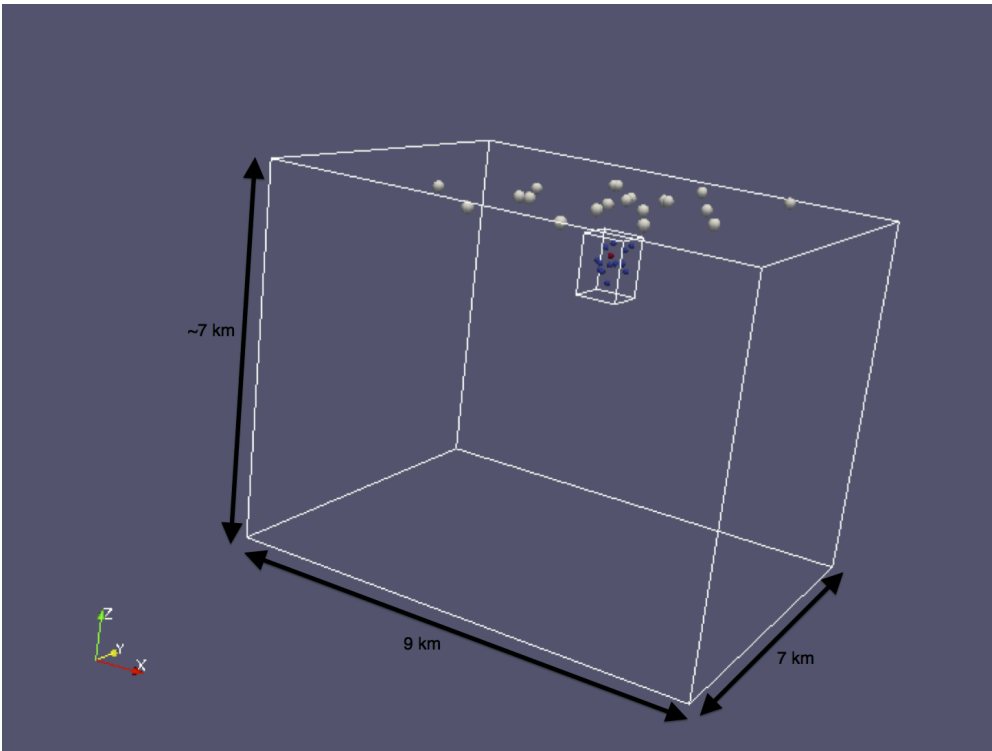


The subclusters can be sorted relative to one another and to the template event.

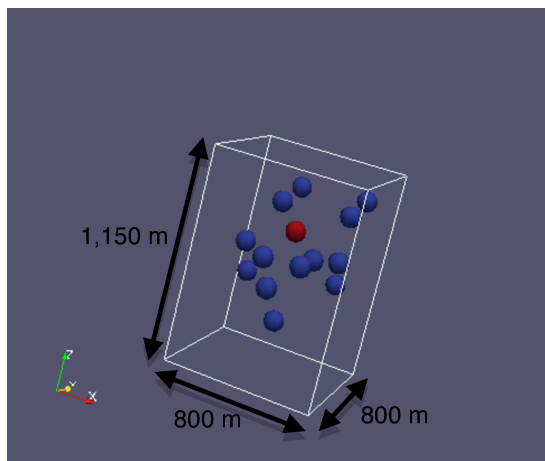
We are able to identify and separate multiple subclusters within the MFP detection group and to synchronize their origin times by observing time shifts.



VSM collapses the computational scale of the problem:
often by several orders of magnitude



This allows fast, full waveform inversion of source focal mechanism, structure and wave propagation.



S4

True MT



Inversion based
on VSM



Deviatoric MT



DC MT

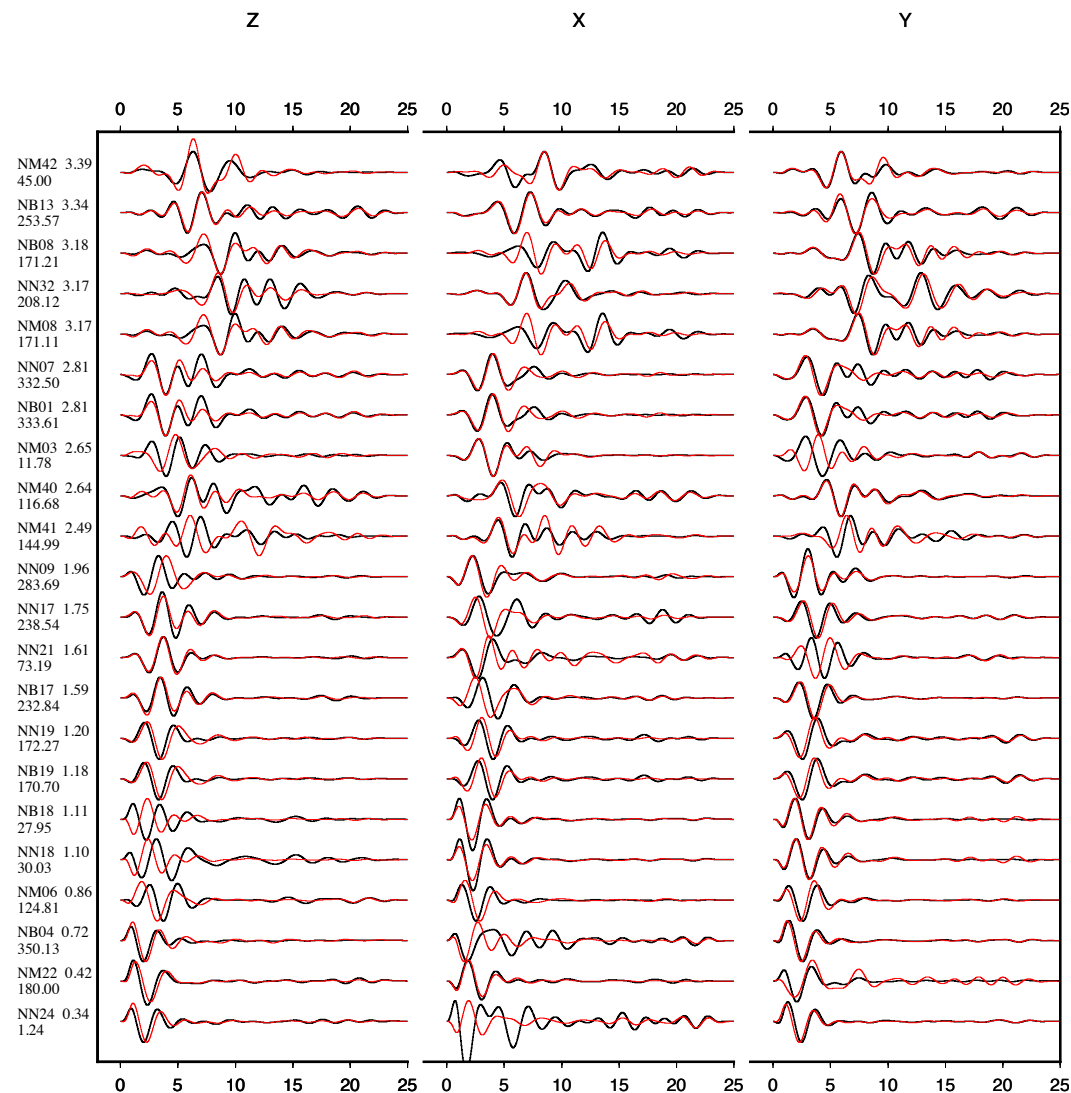
Isotropic (%)

24

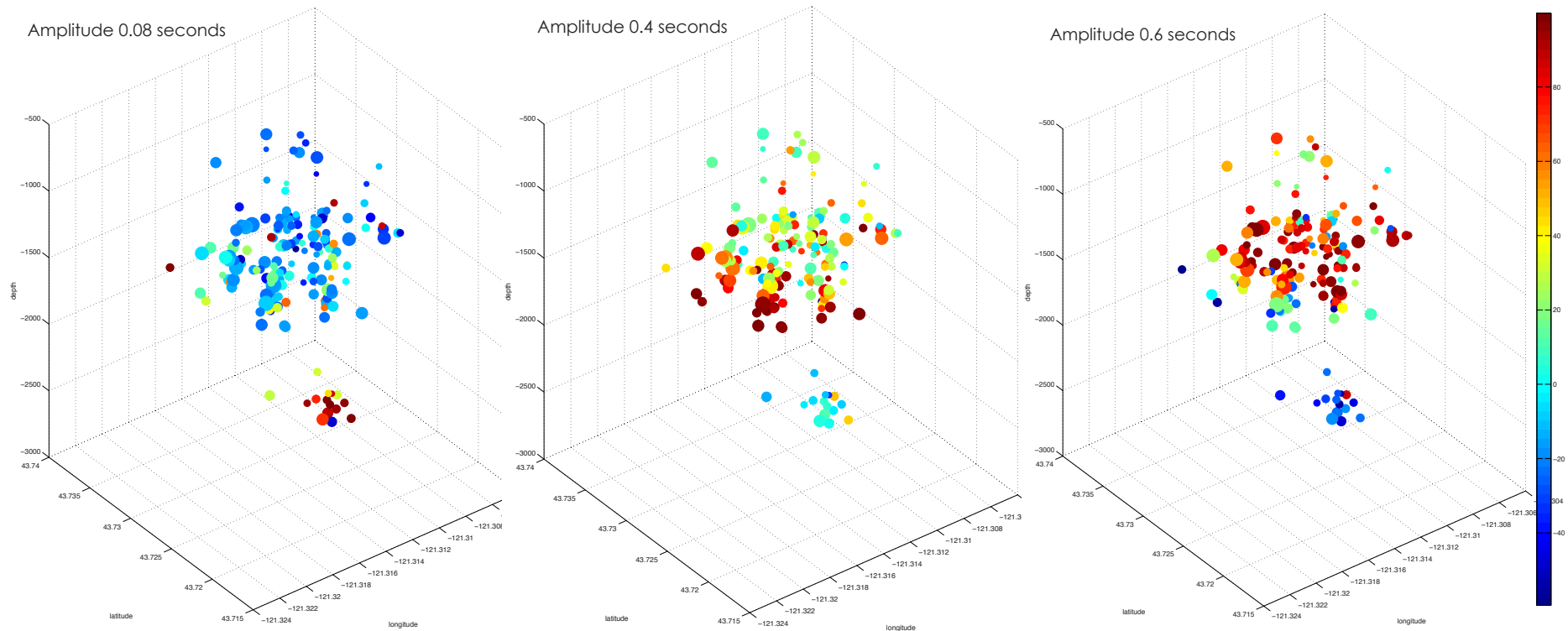
Deviatoric (%)

76

We can recover the focal mechanisms directly by inverting the VSM waveforms



Conclusions



Virtual seismometers allow us to focus directly on this zone of seismicity in tectonically active regions.

Here we are adapting it to regions of microseismicity with the hope of illuminating the subsurface precisely where the pressures are changing. VSM has the potential to image the evolution of seismicity over time, including changes in the style of faulting. Given sufficient microseismicity we can begin to calculate detailed evolution of the wavefield.

Acknowledgements

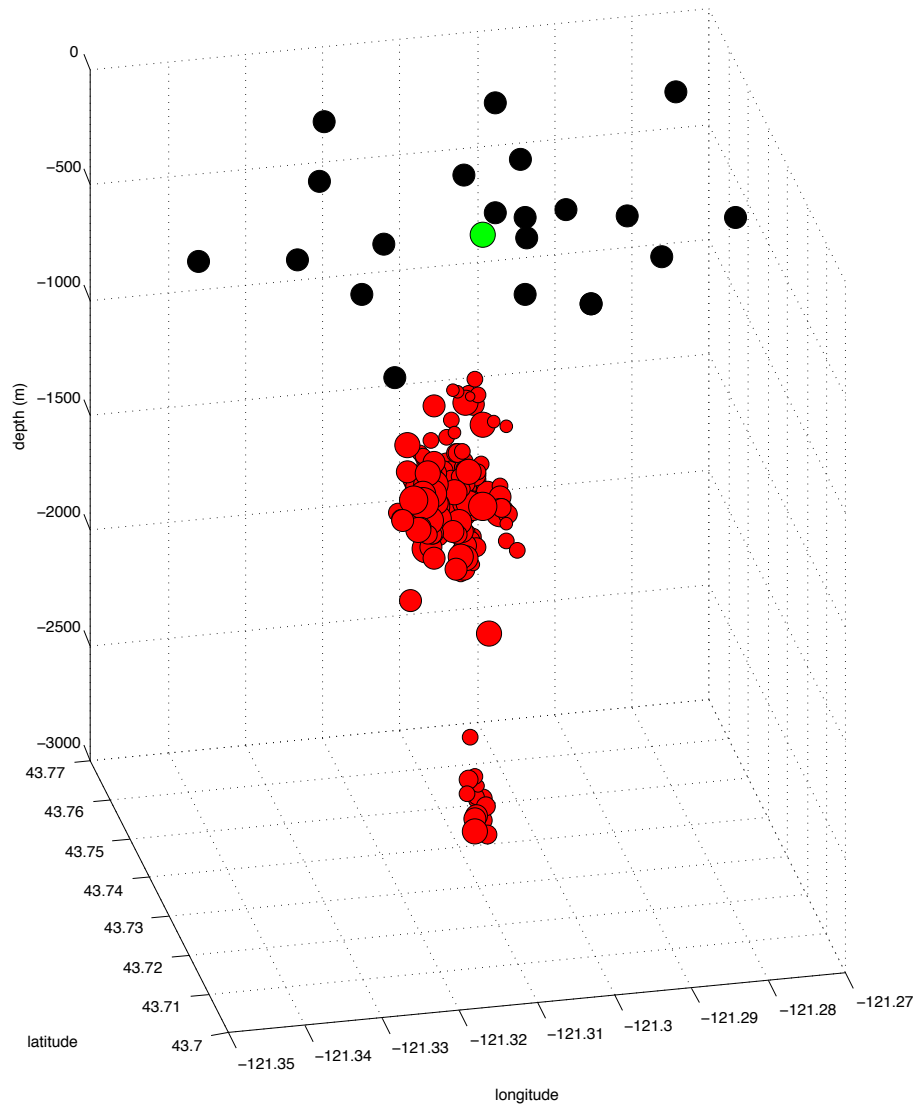
Thanks to AltaRock Energy which conducted the Newberry experiment and provided data for this project and to Foulger Consulting for the catalogs and measurements on the microseismicity.

John Hole provided catalog data on the locations, times and magnitudes of the SSIP sources. We obtained data for the CI network from IRIS and SCEC, for use in the Blanco and Salton Sea studies.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This work was funded by the Laboratory Directed Research and Development Program at LLNL under project tracking code 14-ER-051

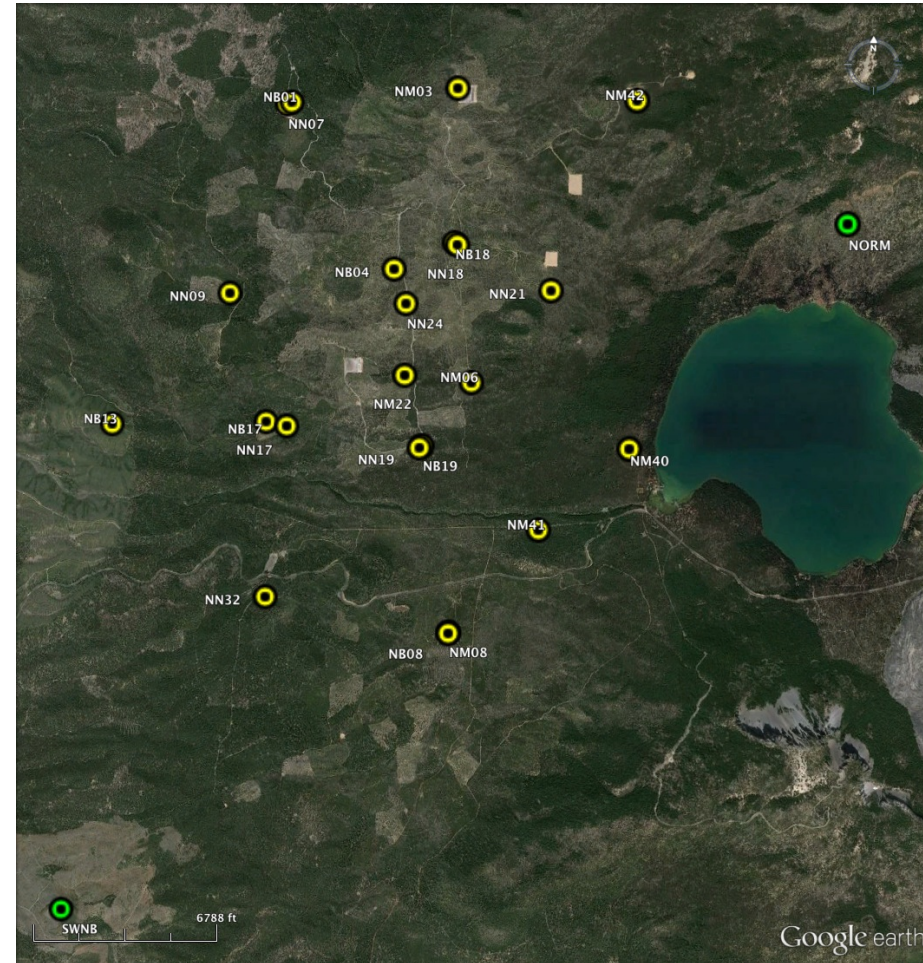
Moving into the near field: Applying VSM to microseismic records (distance between quakes > distance to recording network)

Relocated Microseismicity beneath Newberry



Bayesloc relocation of 180 events identified by Foulger Consulting (October-December 2012).

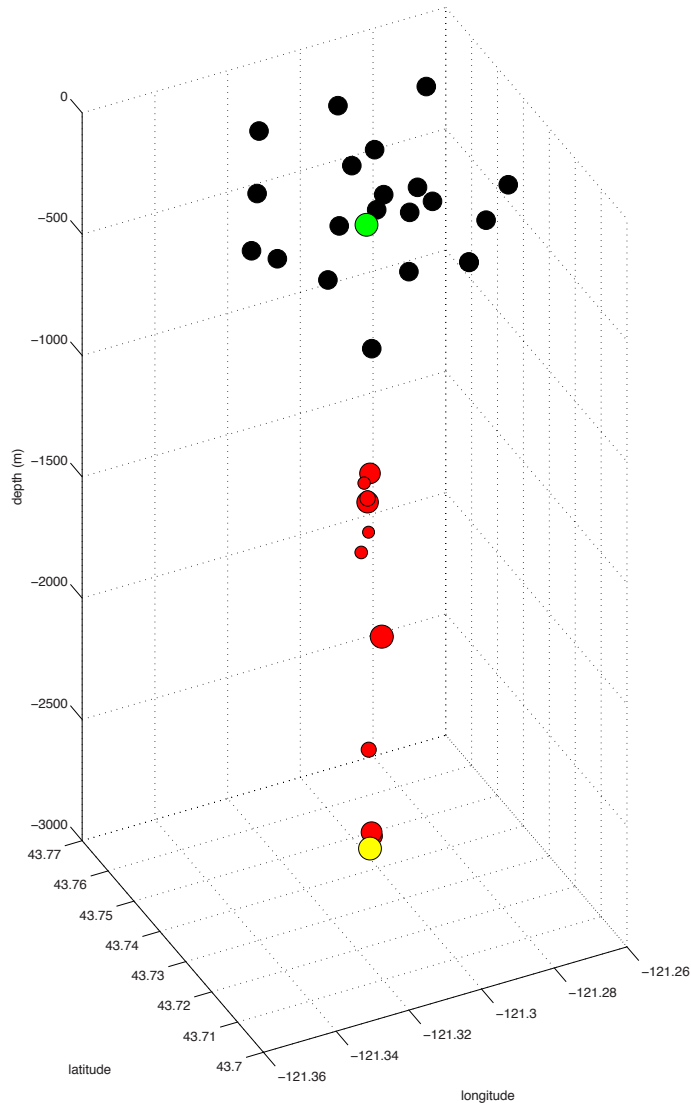
Map of the Newberry experiment network



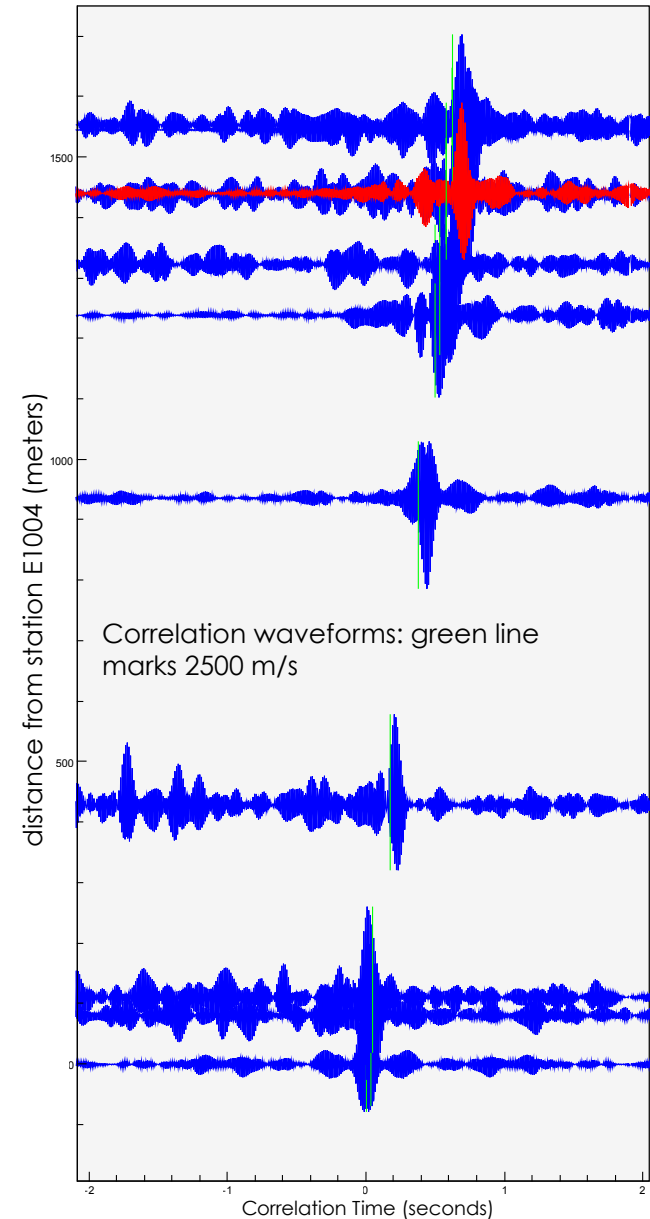
Thanks to AltaRock Energy which conducted the Newberry experiment and provided data for this project.

Example of a microquake as a virtual seismometer

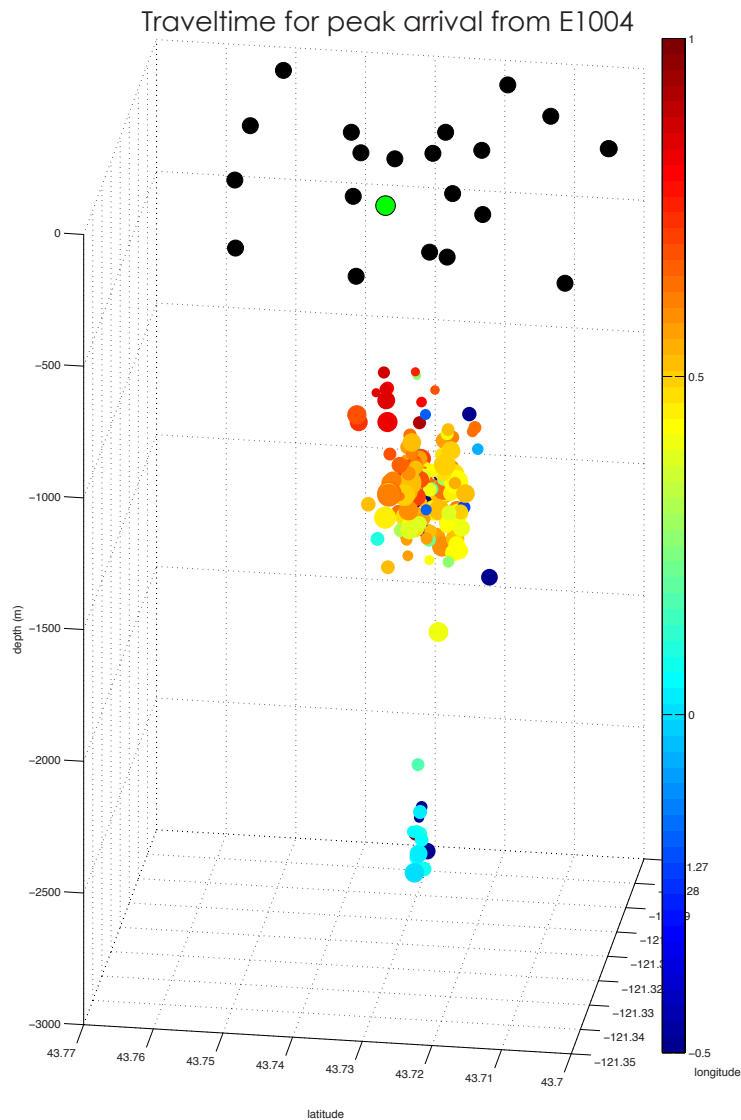
Subset of the Microseismicity beneath Newberry



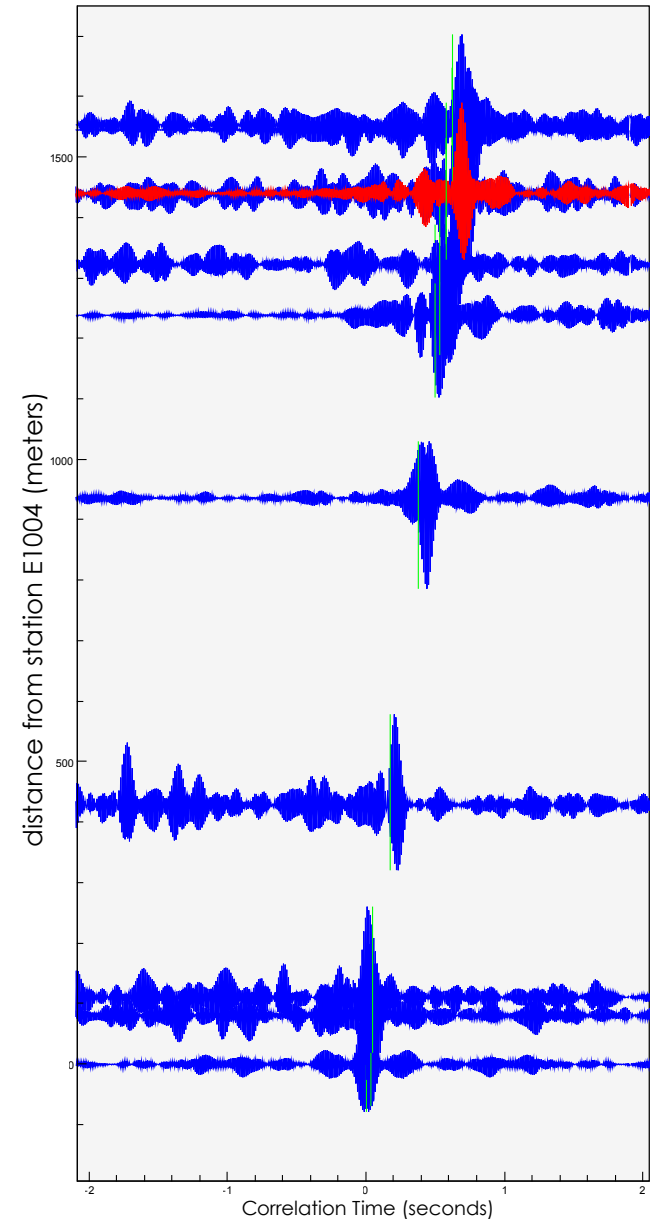
E1004 (yellow) as the reference virtual seismometer recording events along a line pointing towards NN24



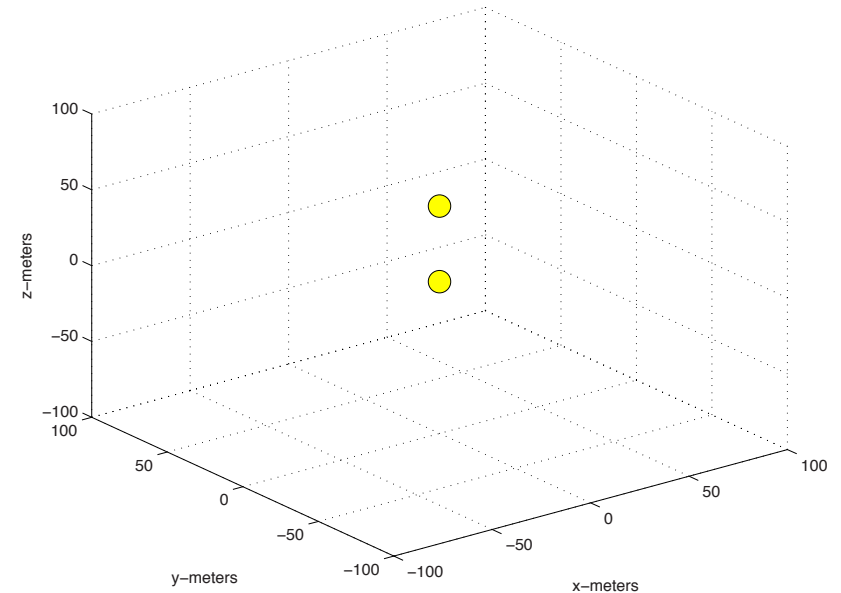
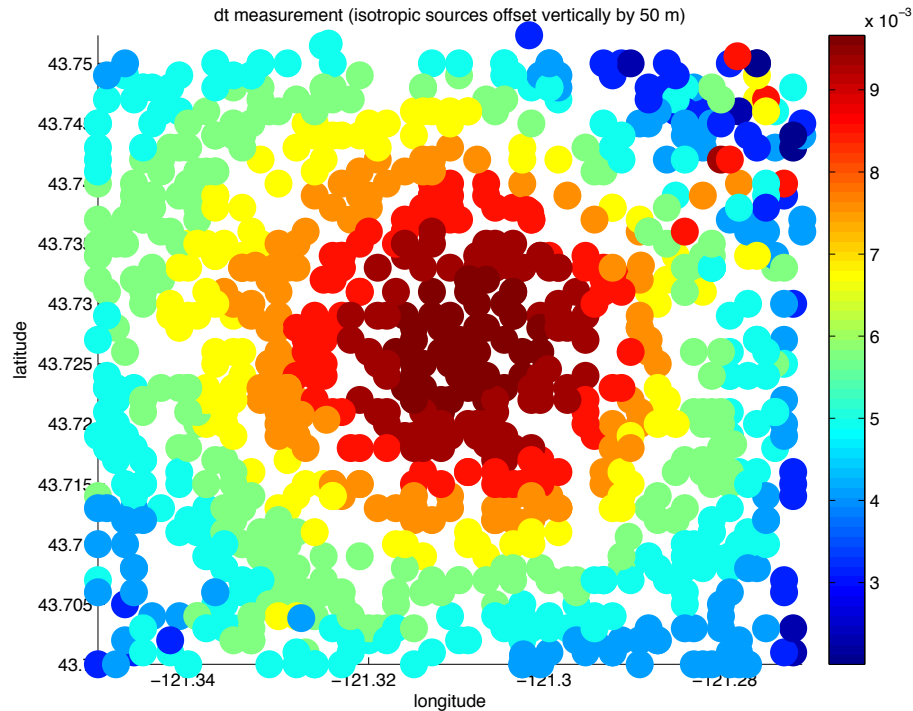
We can begin tracking the waveform propagation through the subsurface



Estimate of the propagation of the seismic waveform from E1004 through the subsurface.



VSM signal is very sensitive to the relative location of the sources



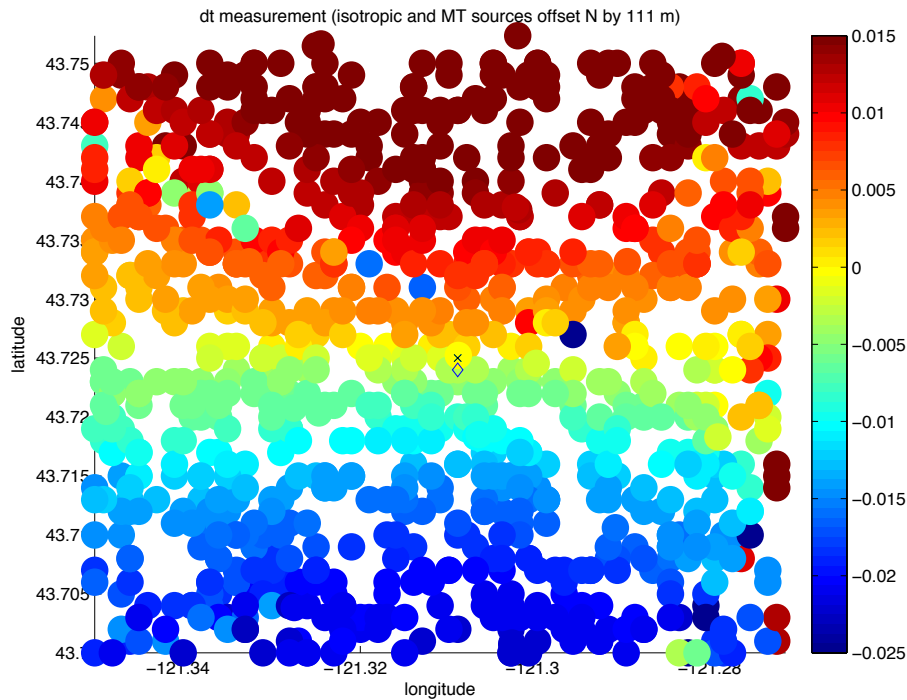
Synthetic case:

Two isotropic sources offset vertically by 50 meters

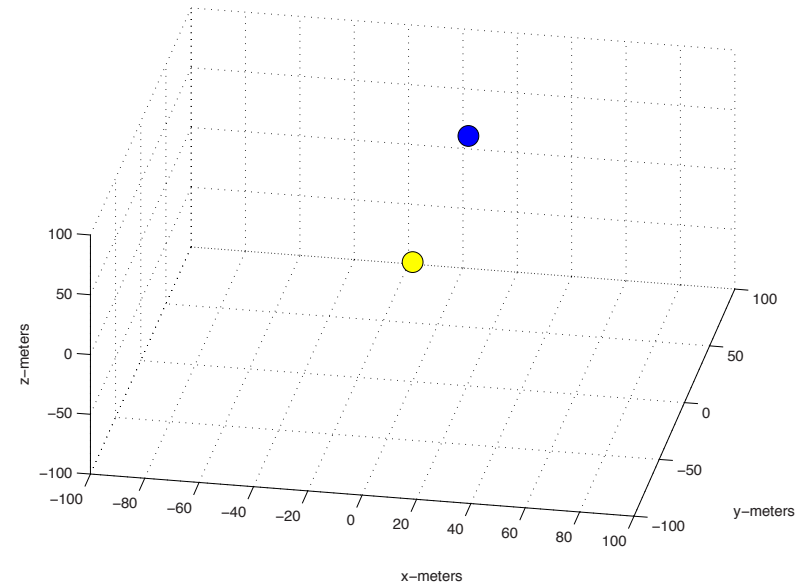
Arrival time measurement:
Two sources offset vertically create a distinctive
bullseye pattern when recorded at the surface.

Understanding the relative offsets between events allows us to make measurements
on the VSM correlations, even when the geometry isn't perfectly in line with the network stations.

VSM signal is very sensitive to the relative location of the sources



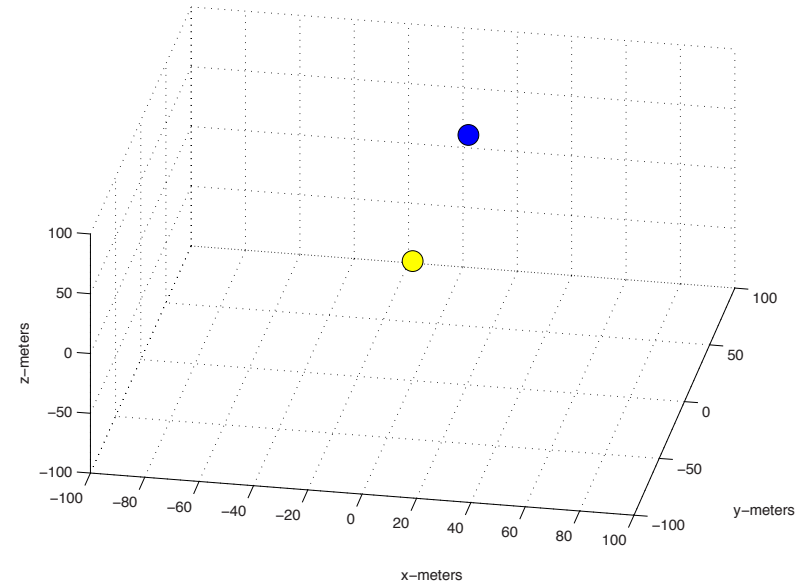
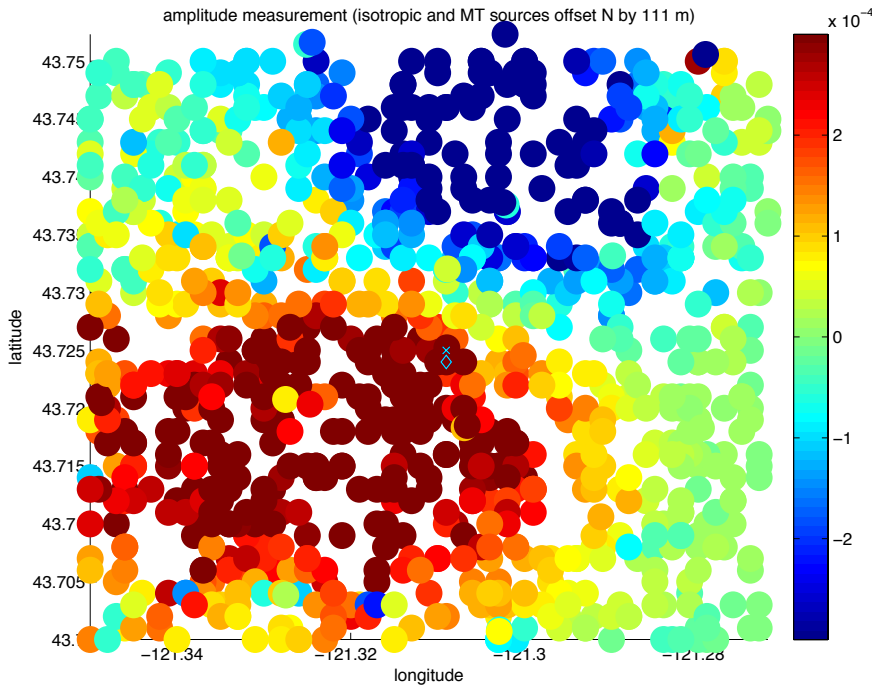
Arrival time measurement:
2 sources laterally offset create a simple
linear pattern.



Synthetic case:
Two sources offset laterally by 50 meters

Understanding the relative offsets between events allows us to make measurements
on the VSM correlations, even when the geometry isn't perfectly in line with the network stations.

Changes in the focal mechanisms can be measured using amplitude of the VSM signal

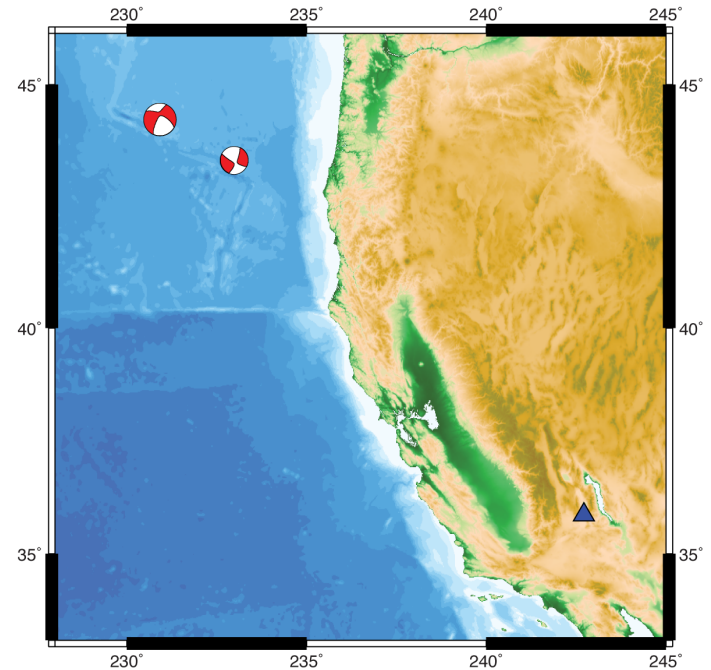
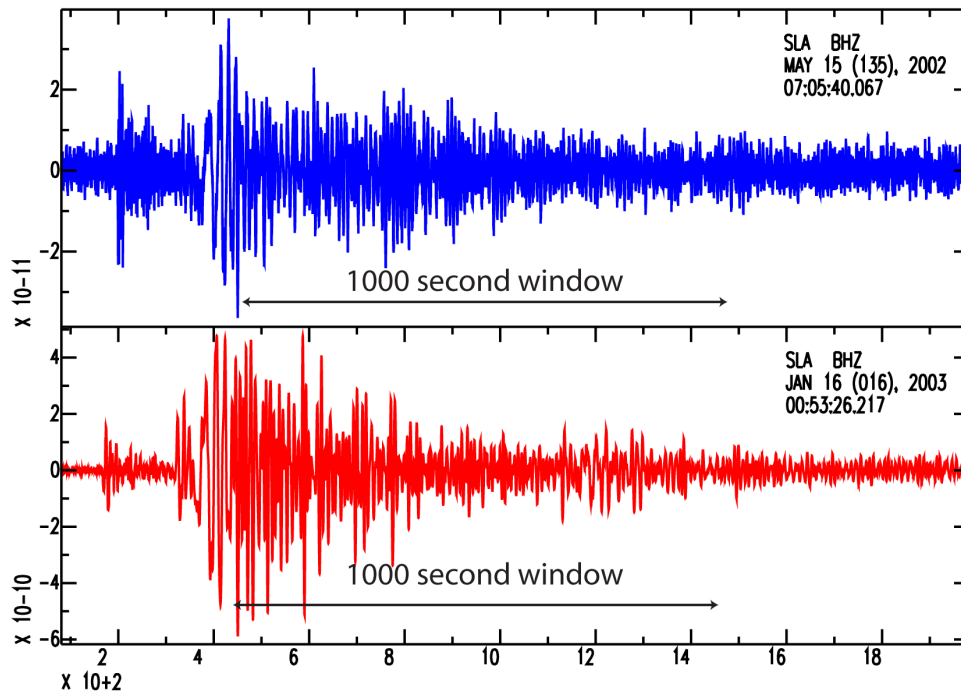


Synthetic case:
Two sources offset laterally by 50 meters
Yellow: isotropic
Blue: DC

Measurement of the Amplitude measurement including the sign of the correlation peak illuminates the relative focal mechanism

Virtual seismograms in the far field (distance between quakes \ll distance to recording network)

How to turn an earthquake into a virtual seismometer.

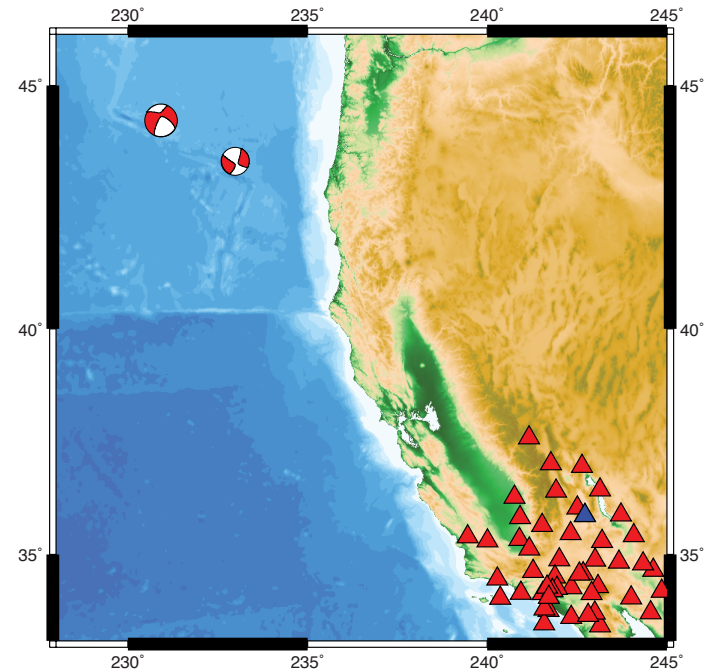
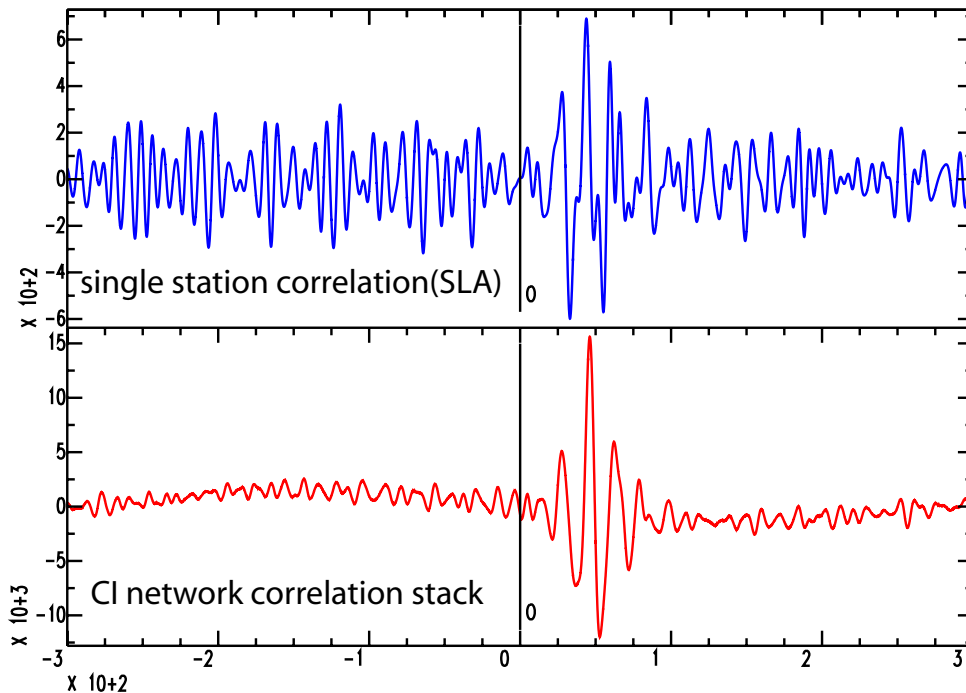


In blue, is the 5.3 Mw, 2002/5/15 earthquake at (43.27, -127.22) . In red is the 6.2 Mw 2003/01/16 earthquake at (44.07 -129.36).
189 km distance between earthquakes.

Virtual seismograms in the far field (distance between quakes \ll distance to recording network)

How to turn an earthquake into a virtual seismometer.

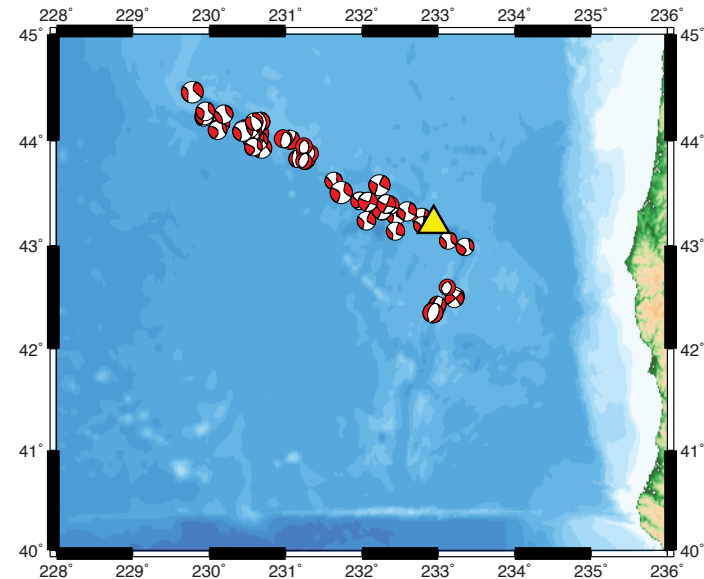
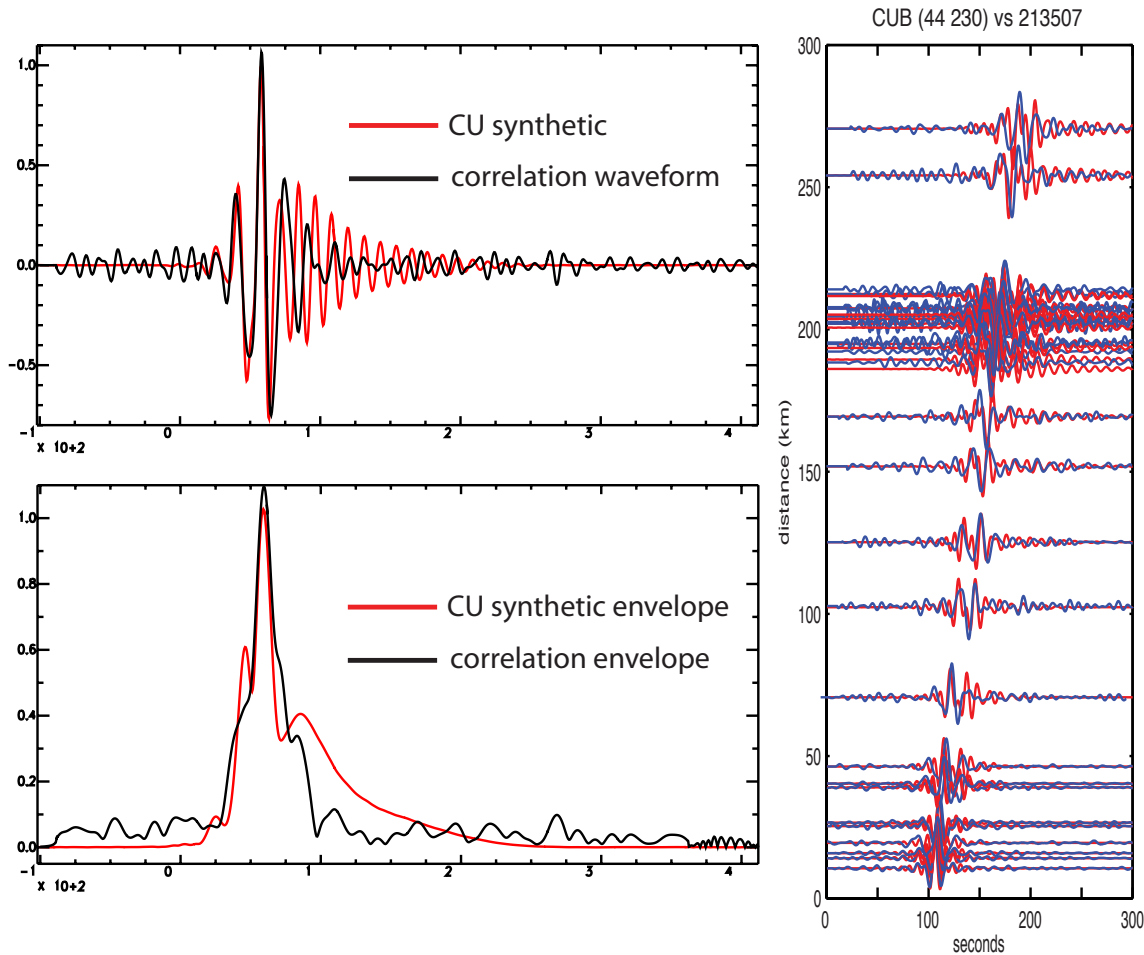
Correlation of the earthquake at (43.27, -127.22) and the earthquake at (44.07, -129.36).



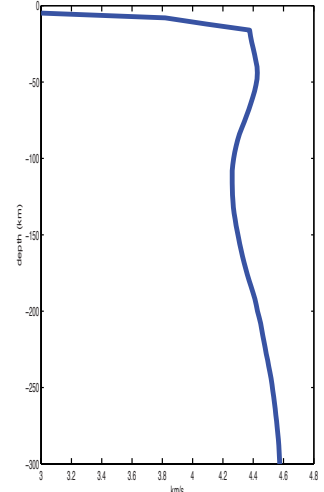
189 km distance between earthquakes.

Virtual seismograms in the far field (distance between quakes << distance to recording network)

The resulting waveforms closely match those predicted by large-scale global models.



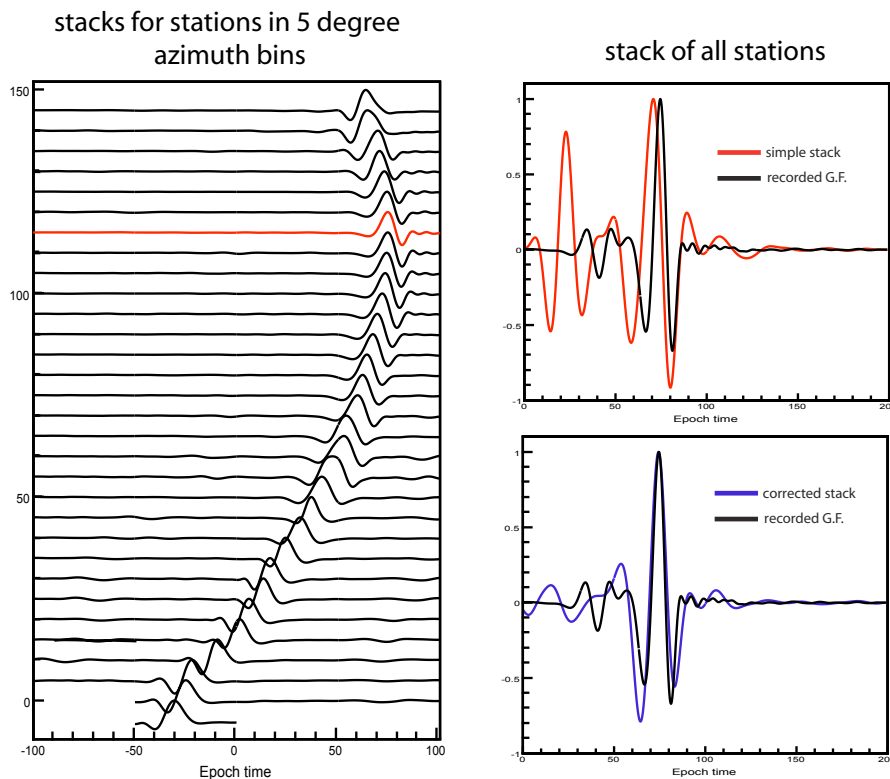
CU Boulder model (44, 230)



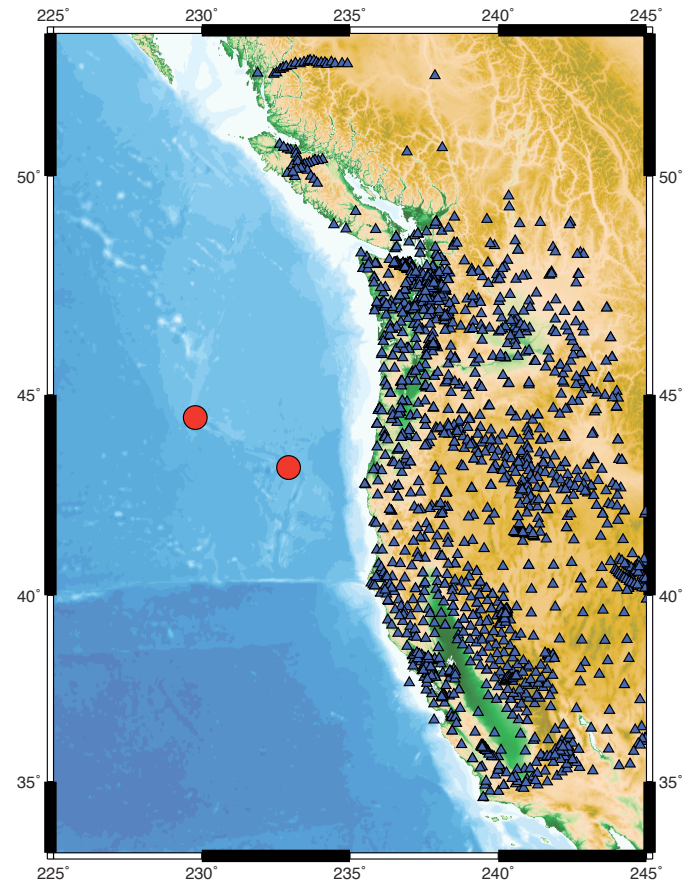
Synthetic seismogram experiment: 2 Isotropic events.

Correlation waveforms vary by azimuth.

Azimuthal corrections are required to obtain the correct waveforms.



azimuth between earthquakes is 117°

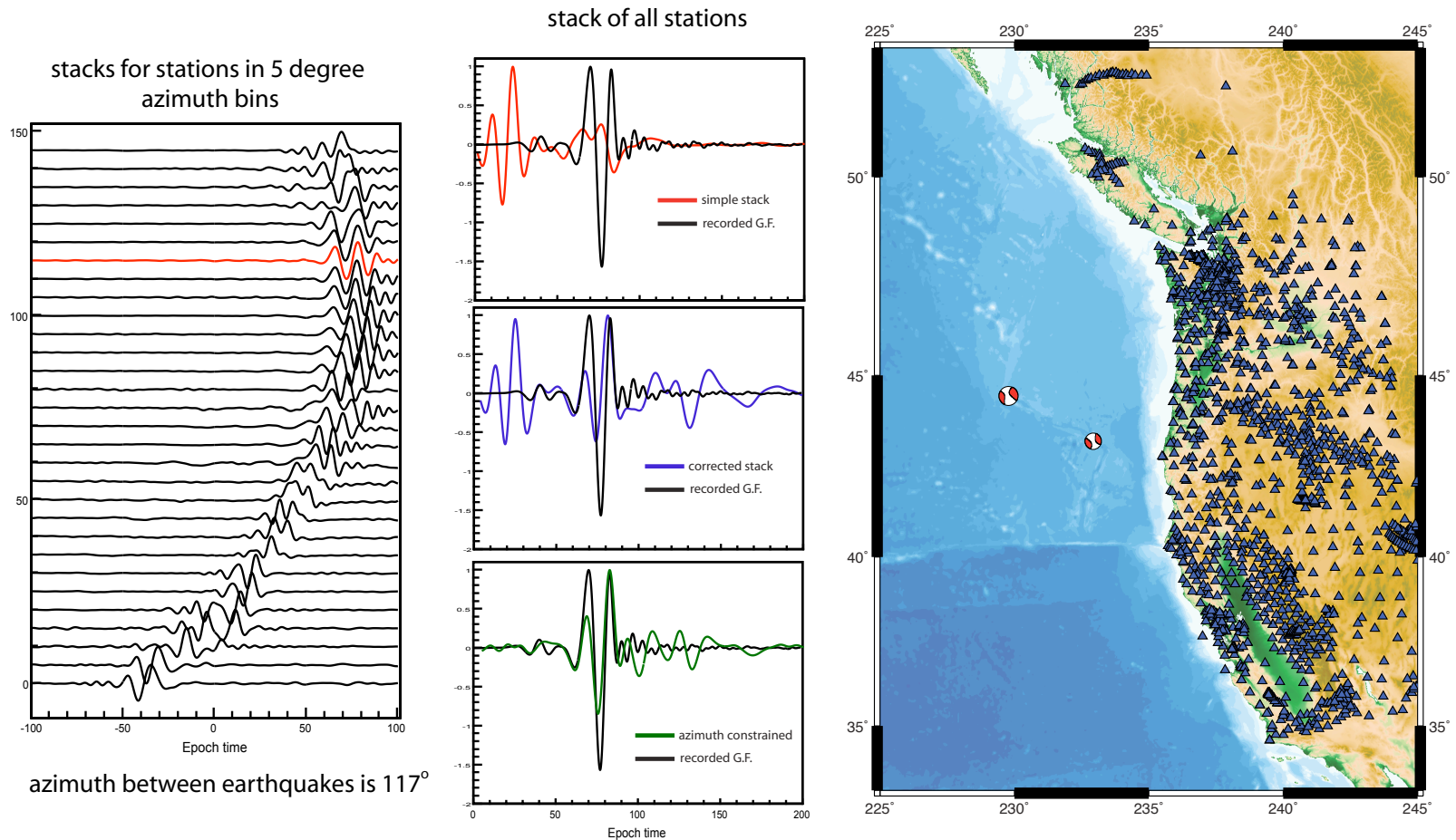


synthetic seismograms calculated using SPECFEM3D_G

Synthetic seismogram experiment: 2 DC events.

Correlation waveforms vary by azimuth with the added complication of source mechanism.

Azimuthal corrections are required to obtain the correct waveforms.



synthetic seismograms calculated using SPECFEM3D_G

Correlation of the seismic coda

Campillo and Paul (2003) used the cross correlation of the diffuse coda recorded at different seismic stations to obtain the Green's function of the Earth between them.

It is straightforward to flip the geometry used by Campillo and Paul and focus instead on the structure between pairs of earthquakes.

Our method, similar to that of Curtis et al. (2009), involves correlating the coda of pairs of events recorded at individual stations and then stacking the results over all stations to obtain the final waveform.

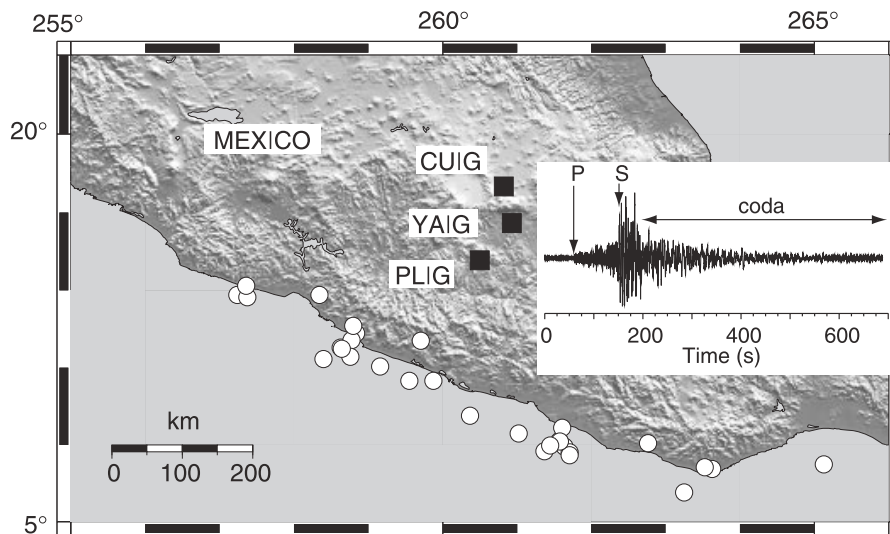


Fig. 1. Location map of the broadband stations CUIG, YAIG, and PLIG of the Mexican National Seismological Network (black squares) and epicenters of 30 earthquakes of the data set (white circles). Inset: An example of a record of one of these events at station PLIG (vertical component).